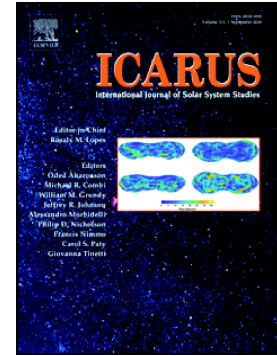


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Potential landing sites characterization on lunar south pole: de-Gerlache to Shackleton ridge region

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ABSTRACT

The lunar south polar region is of specific interest with a much higher probability for finding water ice and volatile resources in the permanently shadowed regions (PSRs). Here, the uneven topography coupled with very low axial inclination of the Moon of $\sim 1.5^\circ$ helps in maintaining a perennial temperature below 110 K in relatively broad areas. Along with the possibility of finding water ice and other volatiles that can be used for future explorations, the south polar region is expected to be compositionally diverse being situated inside the South Pole Aitken Basin (SPA). Though several lunar polar missions were planned, none of them have yet experienced and explored the unique polar environment in-situ. Several sites have been identified majorly based on technical feasibility of landing. The polar sites are challenging to land due to the difficult terrain and limited information about its characteristics. In this study, we selected a ridge region connecting two PSRs: de-Gerlache and Shackleton, and evaluated four sites in that ridge and prioritized them based on the expected scientific outcomes and feasibility to access a PSR for volatile detection and quantification. Our detailed analysis of landing sites is based on terrain characteristics, which include slope, illumination, surface roughness, surface temperature, accessibility to nearby PSRs, compositional diversity, and trafficability. Moreover, multiple micro PSRs have been identified in close vicinity of four landing sites that can potentially trap water ice and other volatiles. We find that the site C1 (-136.2° , -89.406°) situated on the ridge connecting de-Gerlache and Shackleton, and site D (-87.514° , -89°) situated on the rim of de-Gerlache are the most promising sites that can be considered for near future polar exploration missions. These sites provide opportunity of exploration utilizing solar power without compromising on scientific outcomes. Both the sites are found to be in close vicinity of PSR providing opportunities to sample volatiles. The sites C1 and D provide a good alternative to site S (-158.162° , -89.769°) located on Shackleton crater rim, which is considered to be scientifically enriched but technically challenging for landing.

1 INTRODUCTION

The Moon, our celestial companion and the nearest planetary body to Earth is planned to be a base station for ambitious deep-space missions (Cunis et al., 2014; Sherwood., 2019), irrespective of its potentiality for extra-terrestrial science and exploration. In recent times, the research focus is mainly on understanding the lunar polar environment, owing to the advancements in the orbiter-based high-resolution mapping techniques (Chin et al., 2007; Goswami and Annadurai., 2008; Kato et al., 2010; Sundararajan., 2018). Key planetary processes are manifested in the diversity of crustal rocks. Of particular interest is the lunar south pole, where international collaboration and commercial participation converge due to its location within the south pole Aitken (SPA) basin—an ancient and immense impact feature (Wilhelms et al., 1987). This unique region exhibits compositional and structural diversity as this basin based on its size, depth and age is one of the best candidates to get an insight to the Moon mantle material and their composition (Lucey et al, 1998; Petro et al., 2004). Lunar poles also offer accessibility to permanently shadowed regions (PSRs) that can host water ice, characterized by its low obliquity of $\sim 1.5^\circ$ (Spudis et al., 2008; Landis et al., 2022; Kereszturi., 2022) and their intriguing environment. Sampling sites with such distinct characteristics, like the lunar south polar region, can provide answers to the dynamic history of volatile flux over time.

The presence of water on the Moon, particularly in PSRs at the lunar poles, has been a topic of intense research and speculation. The presence of water-ice or water and hydroxyl molecules on lunar surfaces has been discussed in various theoretical studies and observations (Watson et al., 1961; Urey., 1967; Arnold, 1979; Kloos et al., 2019). Indirect evidence for ice in PSRs was provided by the neutron spectrometer on the Lunar Prospector (Feldman et al., 1998, 2001). This interpretation was supported by the results of NASA's Lunar Crater Observation and Sensing Satellite (LCROSS), which impacted into a permanently shadowed region of the southern polar crater Cabeus in 2009 (Colaprete et al., 2010). Supporting evidences were provided from LRO-Mini RF and Earth-based radar instruments (e.g. Nozette et al., 2001; Spudis et al., 2013), which indicated the presence of substantial (≥ 2 m thick) deposits of ice in some PSRs (e.g. Campbell et al., 2006; Starukhina, 2012). Moreover, the Moon Mineralogy Mapper (M^3) data shows the increase in OH/H₂O abundance towards poles (Wöhler et., 2017; Li et al., 2018; Bandfield et al., 2018). Furthermore, M^3 also showed the presence of hematite in certain areas of the south polar region (Li et al., 2020). The occurrence of hematite in a high reducing environment on the Moon is not yet well understood and the detection is yet to be reconfirmed with other datasets (Li et al., 2020; Gawronska et al., 2020). The estimation of depth to diameter ratio of simple craters from polar regions revealed gradual descent in the ratio from lower to higher latitudes suggesting a higher probability of water ice detection in polar regions (Rubanenko et al., 2019). Even though there are several observational evidences regarding the existence of water ice on the Moon, the question regarding its origin and accumulation in PSRs remains unresolved. PSRs are the most interesting locations to verify the proposed hypotheses of volatile transport mechanisms (Urey, 1967; Crotts, 2012) by conducting on-site scientific experiments. Though the lunar poles show great

scientific potential for detailed and systematic exploration, the polar landing is technologically challenging due to their complex topography limiting to narrow regions for exploration, demanding precise landing constrained by variable illumination (De Rosa et al., 2012; Djachkova et al., 2017).

The future of lunar exploration has entered an exciting phase of exploration with several missions planned in this decade (Smith et al., 2020, Zou et al., 2020, Hoshino et al., 2020). Chandrayaan-3, launched this year, successfully landed on a high latitude region of the Moon, with the aim of expanding in-situ studies to explore this region (Karanam et al., 2023). In a promising collaboration with JAXA, India is working on the Lunar Polar Exploration (LUPEX) mission, slated for launch in the coming years. LUPEX's objective is to explore potential water ice resources and volatile compounds in the lunar south polar region using a rover (Ohtake et al., 2021; Hoshino et al., 2020). The upcoming Chang'e 7 mission is equally dedicated to the identification of the exact locations of water ice and volatiles in the ancient craters of the lunar south polar region (Zou et al., 2020). PROSPECT payload launching under NASA's Commercial Lunar Payload Services (CLPS) mission will assess lunar regolith near to the lunar south pole up to 1 m deep, determining volatile presence, abundance, and origin through elemental and isotopic analyses (Boazman et al., 2022). NASA's Artemis 1 and Artemis 2 missions are strategically planned to identify potential landing sites and traversing paths for crewed missions, with a focus on getting as close as possible to PSRs. Their objective is to systematically gather Moon samples, expanding the sample database from equatorial regions to polar regions (Angelopoulos 2014, Smith et al., 2020). India has recently joined the Artemis program, solidifying its commitment to the best practices and norms in space exploration. A successful landing on a high latitude region has demonstrated India's capabilities of scientific exploration of the lunar polar regions, which is technically challenging for landing due to its topography but at the same time scientifically enriched due to the probable presence of volatiles including water ice.

In light of the growing focus on the lunar south polar exploration, this work aims to conduct an integrated and comprehensive study of a ridge stretching from the eastern rim of de-Gerlache crater (88.5° S, 87.1° W) to the western rim of Shackleton Crater (89.9° S, 0.0° E) (De Rosa et al., 2012), also known as the 'Connecting Ridge' to demonstrate the potentiality of this region to harness the maximum scientific outcomes and also contrarily to exemplify the technical limitations. This elevated area between de-Gerlache crater and Shackleton crater is of high interest and in consideration for LUPEX and Artemis landing missions (Bhattacharya et al., 2022; Bernhardt et al., 2022). A series of studies carried out on the connecting ridge between Shackleton and de-Gerlache based on the critical requirements of illumination of about 70% in order to identify optimal options of landing (Gläser et al., 2018; Flauhat et al., 2020). Within the connecting ridge, we focus on the detailed characterization of four landing sites as marked in Figure 1. Three of these sites (S, C1, C2) coincide with Gläser et al., (2014) study, and the fourth site (D) is situated on the rim of the de-Gerlache crater. The Artemis landing site 011 (Smith et al., 2020) is also located on the de-Gerlache rim but the site D (Fig. 1), proposed in this work, is primarily selected based on the illumination condition similar to the other three sites. The studies on sites S, C1 and C2 were mainly conducted on

understanding the illumination over several future mission cycles (Fincannon, 2007; Mazarico et al., 2011; Koebel et al., 2012; Speyerer and Robinson, 2013, Gläser et al., 2018), but the site D was not studied in detail. Our main objective is to study all four sites on the connecting ridge of Shackleton and de-Gerlache craters by integrating both technical and scientific aspects on a site-specific basis.

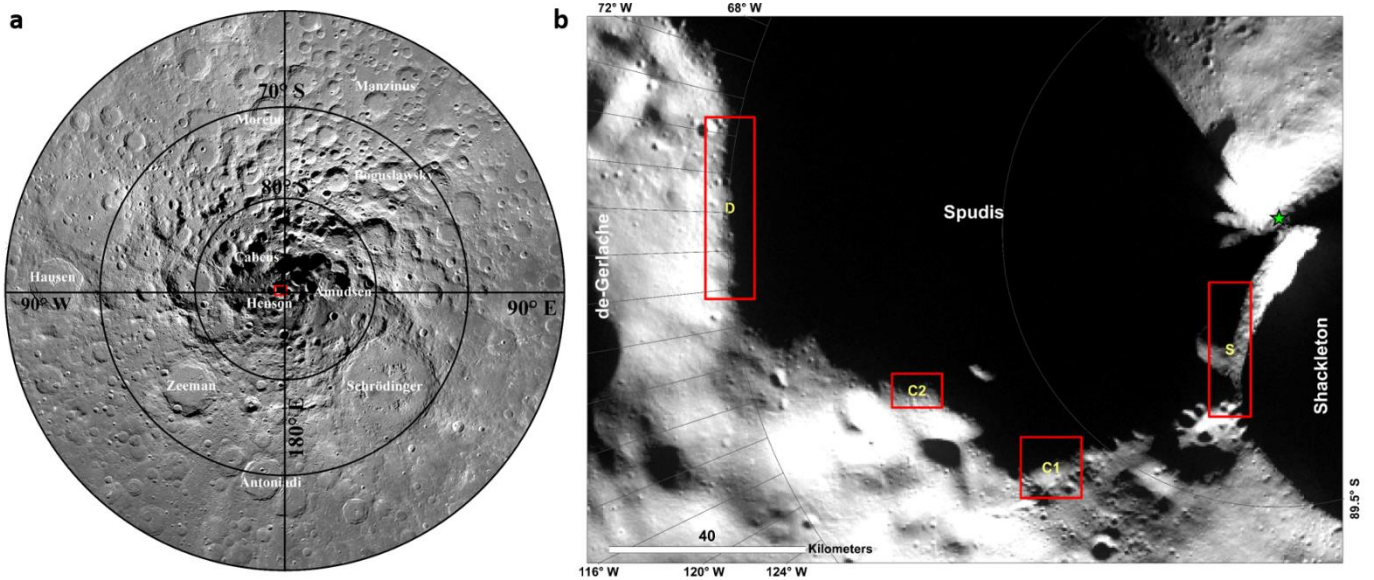


Figure 1. (a) Lunar south pole with the landing locations in red rectangle; (b) Spatial extent of selected landing sites situated on the connecting ridge of the Shackleton and de-Gerlache craters. The site S is on the Shackleton rim, sites C1 and C2 are situated on the connecting ridge, and the site D is situated on the de Gerlache crater rim. The lunar south pole is represented by a green star. The base map is LRO WAC mosaic (Robinson et al., 2010)

1.1 Geological setting of the selected sites

The selected landing sites, shown in Figure 1, offer a unique opportunity to explore the polar environment. These landing sites are within the outer rim of the SPA basin, ensuring more insights into this oldest impact basin (Wilhelms et al., 1987) through in-situ exploration mode. These landing sites span three distinct geological epochs in accordance with the lunar chronology system proposed by Wilhelms et al., (1987) (Supplementary Figure S1). The entire connecting ridge region belongs to the Pre-Nectarian period and is probably covered by the remnants of the SPA impact event (Spudis et al., 2008). Site D, conversely, is representative of the Nectarian period, its formation is intimately tied to the impact event that gave rise to the de-Gerlache crater (Wilhelms et al., 1987). Site S belongs to the youngest unit of the region, the Eratosthenian period, during which the Shackleton crater was formed (Wilhelms et al., 1987). The de-Gerlache and Shackleton craters, along with the ridge between them, hold a high potential for harboring water ice deposits due to its favorable topography and thus, are ideal for preserving water ice and volatile compounds (Flauhat et al., 2020; Brown et al., 2022; Kereszturi et al., 2022). The geological significance of the connecting ridge lies in its location between two prime PSRs, implying that it could contain ejecta

material from the formation of both craters- de-Gerlache and Shackleton, making it scientifically intriguing (Bernhardt et al., 2022).

Moreover, the ridge and its immediate environments exhibit spectroscopic signatures indicative of hematite, a mineral of increasing interest in lunar geological studies (Li et al., 2020). Furthermore, the intersection of Tycho ejecta rays with the connecting ridge, as delineated by the Lunar Orbiter Laser Altimeter (LOLA) albedo and roughness maps, augments the region's scientific potential (Bernhardt et al., 2022; Denevi et al., 2023).

Photogeologic studies of the Shackleton crater reveals the presence of blocks of ancient crustal material, including purest anorthosite (PAN) in its crater walls (Yamamoto et al., 2012), apart from ejecta and boulders distributed near the vicinity of the crater (Gawronska et al., 2020). If blocks of exposed PAN can be located and analyzed on in-situ mode, understanding of the origin of PAN in the lunar crust, the production of massifs by the SPA basin-forming impact, and the subsequent geologic evolution of the region will be greatly improved (Gawronska et al., 2020).

The location S (-158.162° , -89.769°) in Figure 1 is studied in detail by Gläser et al. (2018) with an areal extent of 17.5 km^2 mainly considering the illumination conditions and considered to be one of the highest priority landing sites for future missions like Artemis and Lupex (Bernhardt et al., 2022; Saiki et al., 2021). The site is set as a high priority landing site due to its proximity to Shackleton crater with a larger PSR in its vicinity. Shackleton crater is considered as an important target in terms of volatile exploration (Flahaut et al., 2019; Gawronska et al., 2020) and was considered to have excavated the eastern part of 'Connecting Ridge' (Stopar and Meyer, 2019). However, due to steep slopes around it ($>30^\circ$), exploring its interior using a small scale rover like Chandrayaan-3 is challenging. The site C1 (-136.2° , -89.406°) is located along the connecting ridge, which is an irregular massif of pre-Nectarian age and is considered to be a part of the SPA impact basin (Spudis et al., 2008). It is an interesting site as it is almost equidistant from Shackleton and de-Gerlache craters and may carry ejecta of both. The site C1 might be considered as a geological boundary substantiated by the crater density difference between old and young craters present in the region (Scoville, 2022). The region is about 11.5 km^2 in area and was also studied by De Rosa et.al, (2012) and Gläser et al., (2018). The site C2 (-113.771° , -89.283°) is same as the area mentioned in Gläser et al., (2018) with an areal extent of 5.2 km^2 . The site C2 has the smallest areal extent out of all other landing sites and is also situated on the connecting ridge. One of the Tycho ejecta rays passes along the western side of the site C2 (Bernhardt et.al., 2022), providing a unique opportunity of investigating the Tycho ejecta material along with de-Gerlache and Shackleton craters ejecta. The site D (-87.514° , -89.003°) is located on the rim of the de-Gerlache crater, specifically at the place where the connecting ridge merges with the de-Gerlache crater rim. The region has an areal extent of 27 km^2 . The site D offers an opportunity to explore the de-Gerlache crater and several meter scaled PSRs that are located along the east of the site. The site also hosts several fresh craters giving an opportunity to sample and systematically study local stratigraphy through in-situ measurements. Geomorphologic maps prepared for the upcoming Artemis missions (Bernhardt et al., 2022,

Angelopoulos, 2014) also covered the selected landing sites in this study and depicted interesting geomorphological conditions at site C1 and near the Shackleton crater.

2 Datasets and Methods

Our geotechnical and scientific analysis of the landing sites, shown in Figure 1, are based on the high level data products obtained from Chandrayaan-1, Chandrayaan-2 and LRO orbiters as listed in Table 1. Along with this, we also used the geomorphological and polar terrain maps of the south polar region in order to understand the scientific importance. Geographic Information System (GIS) environment of ArcGIS software has been used for integrating multiple datasets listed in Table 1. All the data sets were projected in south pole stereographic projection, and a hill-shaded LOLA DEM was used as a base for generating the maps presented in this study.

Table 1. The high level data products used in this work are from Chandrayaan-1, Chandrayaan-2 and LRO missions. The spatial resolution and the source of data products are also added. Please refer to the reference added for each product used in this work for further details.

Data product/maps	Mission	Spatial resolution	Source	References
Lunar Reconnaissance Orbiter Camera-Wide Angle Camera (LRO- WAC) Mosaic	Lunar Reconnaissance Orbiter (LRO)	100 m	USGS	Robinson et al., (2010)
Lunar Reconnaissance Orbiter Camera-South pole Narrow Angle Camera (LRO- NAC) Mosaic	LRO	1 m	USGS	Robinson et al., (2010)
LOLA Digital Elevation Model (DEM)	LRO	5 m	USGS	Smith et al., (2010)
Polar Illumination Map derived from LOLA	LRO	60 m	PDS	Mazarico et al., 2011

Earth Visibility Map derived from LOLA	LRO	60 m	PDS	Mazarico et al., 2011
Diviner Lunar Radiometer Experiment (DLRE) Minimum, Maximum, Summer and Winter Average Bolometric Temperature Maps	LRO	240 m	PDS	Williams et al.,(2019)
Diviner Lunar Radiometer Experiment (DLRE) Hourly Temperature Data	LRO	240 m	PDS	Williams et al., (2019)
Moon Mineralogy Mapper (M ³)	Chandrayaan-1	140 m	PDS	Green et al., (2011); Pieters et al., (2009)
Orbiter High Resolution Camera (OHRC)	Chandrayaan-2	0.25 m	ISRO- PRADAN	Dagar et al., (2022)
Geomorphology map of south polar region	LRO	1:8000	-	Bernhardt et al., (2022)
Polar Terrain Type Maps	Model based outcomes	590 m	https://kevincannon.rocks/lunarmining/	Cannon and Britt (2020)

We used a LOLA DEM of the lunar south polar region at 5 m spatial resolution (Smith et al., 2010) for the morphological analysis based on the derived products; elevation, slope and surface roughness. LOLA is the laser altimeter onboard the LRO that gives elevation data at different resolutions. We used a subset of the LOLA DEM that includes all four landing sites shown in Fig. 1(b). We added contour lines at 250 m intervals on the LOLA DEM to visualize the changes in elevation within each site in consideration. A

contour line joins the points of equal elevation or height above a given reference level and essentially represents the steepness of the terrain along with the direction in which the land is sloping. The closer contour lines are indicative of the steeper slopes. Slope evaluation is necessary for landing site characterization in order to ensure the stability of the lander during touchdown. The baseline used for the slope map is of 10 m. For any point in the DEM, slopes along the east-west and north-south directions are calculated based on the distance and elevation difference of two neighboring grid cells and the square root of the sum of their squares is calculated as the maximum slope of that point (Wu et al., 2020). The illumination conditions at the polar regions differ considerably from the rest of the Moon due to its small obliquity of 1.54° . Several studies have specifically simulated illumination conditions centered on the poles to determine illumination conditions over several future mission cycles (Fincannon, 2007; Mazarico et al., 2011; Koebel et al., 2012; Speyerer and Robinson., 2013; Gläser et al., 2014; Gläser et al., 2018). In this work, we incorporate LOLA-based average illumination map of the south polar region in a percentage scale for quantifying the area of the highest illumination for each landing site and also to identify areas with zero percentage illumination. we also extracted illumination at 2 m elevation for each landing site considering the lander's solar panel height based on Gläser et al., (2018) approach. The illumination conditions for the sites S, C1, and C2 are given in Gläser et al., (2018) and in the same way simulated for site D. Gläser et al., (2018) used LOLA DTMs sampled at 20 m/pixel for the simulation of polar illumination for a full lunar precession cycle of 18.6 years covering all seasonal and orbital illumination effects. We used the LOLA DEM also to estimate the topographic roughness by taking the ratio of differences; 'Mean height-Minimum height' to 'Maximum height-Minimum height'. The roughness value range is from 0-1, where 0 represents a comparatively smooth surface and 1 represents comparatively rough terrain with obstacles. The illumination map along with slope and roughness maps prepared using the LOLA DEM were overlaid to generate a trafficability map covering all the landing sites.

Direct radio communication with Earth is necessary if there is no relay satellite launched to support relay communication (Zou et al., 2022). The Earth visibility values for each location on Moon was calculated by comparing the elevation of the local horizon to the elevation of the Earth at a given time by simulating the trajectories of Earth over local horizon (Mazarico et al., 2011). The Earth visibility values range between 0 (never visible) and 1 (always visible), and indicate the percentage of time steps where any fraction of the Earth disc was visible at each pixel.

For understanding the geomorphic characteristics of the landing site, we rely on a small-scale geomorphological map, proposed recently by Bernhardt et al., (2022) for Artemis III landing areas of interest. The detailed maps prepared by Bernhardt et al., (2022) includes partially the Shackleton-de Gerlache ridge region. We applied the approach proposed by Bernhardt et al., (2022) to the landing sites in consideration here and prepared geomorphological maps of the landing site as per the geomorphic unit classification of Bernhardt et al., (2022). We used LROC-NAC (Robinson et al., 2010) and Chandrayaan-2

OHRC images (Dagar et al., 2022) for the identification of fresh craters and boulders within a landing site and for demarcation of different landform units.

The diurnal temperature variations and the variations of temperature across seasons for each landing site were studied using DLRE maximum, minimum, and average summer and winter bolometric temperature data. The annual temperature variation can be used as a proxy to locate PSRs. The same data outcomes were used to formulate a PSR map to identify potential PSRs around each landing site. We define a set of parameters to identify volatile-rich PSRs, also known as micro cold traps (Hayne et al., 2021), around the landing locations. The main parameter is the temperature, which plays a major role in the distribution and localization of volatiles. Volatile ices are usually stable at temperatures as high as 54 K (Zhang et al., 2009), which is the sublimation temperature of CO₂ ice. Volatiles such as N₂ ice, CO ice, Ar, CH₄ ice, Kr, and Xe usually have a sublimation temperature below 40 K. The sublimation temperature of H₂O ice is around 100 K (Flauhat et al., 2020), which is the annual average temperature in most of the PSRs. If the temperature of a specific region is known, the kind of volatiles that are stable in that particular environment can be determined. Several PSR maps are available in the public domain, which are mainly prepared on the basis of shadowed regions in LROC-WAC/NAC images (Bernhardt et al., 2022), very low illuminated regions as well as the Diviner derived temperature-based PSR maps (Williams et al., 2019). We integrated the information from the illumination and temperature datasets in order to identify localised PSRs. The PSR defined here is with a Diviner average bolometric temperature below 100 K and illumination less than 2%. The probable depth of ice accumulation in each of the PSR, identified using PSR map, was found through the polar terrain map (Cannon and Britt, 2020).

Spectral analysis of the landing sites was carried out using M³ onboard Chandrayaan-1 (Pieters et al., 2009). The M³ imaging spectrometer measured the spectral range from 430 nm - 3000 nm with 85 spectral channels and 140 m spatial resolution on global mode. The 2500-3000 nm spectral range of M³ was mainly focused on hydroxyl/water detection. M³ Level-2 reflectance data corresponding to all 4 landing sites were analyzed after removing noisy data for finding OH/H₂O and other mineral signatures. The sites S, C1, C2, and D were covered within a total of 63 M³ images. We created a subset of the data based on the corner coordinates and quality of the reflectance spectra by discarding spectra of poor signal-to-noise ratio (SNR). The M³ data is used for understanding OH/H₂O distribution and local mineralogy.

For a successful soft landing and in-situ measurements through lander and rover platforms, appropriate landing site selection and characterization is one of the most important aspects. In general, such selection is mainly driven by rover and lander specifications. We considered nominal operational constraints and ranked some of the important landing sites from the lunar south polar region. Each landing site area shown in Figure 1 is bounded considering a broader comparatively flat area (De Rosa et al., 2012; Sun et al., 2014; Liu et al., 2021). We evaluated each landing site (Fig. 1) in terms of variations in slope, illumination conditions, and

roughness as these parameters are the geotechnical constraints that determine landing and roving feasibility. The scientific importance of each landing site is also assessed and combined with the geotechnical analysis considering that the scientific returns after landing is equally important as the landing safety. Our approach here is qualitative and will be further refined when cm scale higher resolution images of the region will be available. The geotechnical evaluation of each landing site is qualitatively categorized as ‘excellent’/‘good’/‘poor’ depending on the maximum to minimum variations of individual parameters. The general set of the parameters are based on previous studies by De Rosa et al., (2012); Sun et al., (2014); Liu et al., (2021).

3 Results

Geotechnical Analysis of Landing sites

The geotechnical analysis of landing sites is based on the evaluation criteria explained in the section 2. Figure 2 shows the landing area and variation of each of the parameters discussed in detail in subsequent subsections and Table 2 summarizes the average values and corresponding ranking for each landing site in consideration.

3.1. Topography and Slope

The elevation variations within the landing sites are shown in Figure 2a, and slope variations corresponding to elevation variations are shown in Fig. 2b. Though for optimal landing sites the slope is constrained to less than 7° (Mitrofanov et al., 2012), the range has been expanded to 15° for rover operations (Bickel et al., 2022) and in some studies it extends up to 25° (Lemelin et al., 2014). The slopes above 15° are considered as unsuitable for both landing and roving as steeper slopes could cause the lander/rover to capsize. For our study, we constraint the slope suitable for landing at 8° and 14° for rover operations. If at least 60% of the area contains slopes less than 14° for rover operations and about 40% of this area having slopes less than 8° for landing, the site is categorized to ‘excellent’, otherwise to ‘poor’ based on only the surface slope variation. A priority scoring based on only slope for each landing site is given in Table S1. The percentage area of slope less than 8° and less than 14° are also included in Table S1.

According to the slope map (Fig. 2b) and parameters listed in Table S1, the sites C1 and C2 are categorized as ‘excellent’ for landing and traverse planning. Figure 2b shows the maximum slope values are relatively high (about 45°), but these steep values are confined only to small crater walls that can be avoided while planning rover traverses. About 30% of the area of the entire C2 site show slope less than 8° . Site C2 have a maximum elevation of 1693 m and with an average of 1594 m and the entire area of C2 site is covered in a single contour of 250 m interval, indicative of less topographic variations within the site. Site C2 also offers maximum safe area for landing within the slope constrained limits. The site C1 is the highest elevated landing site among all four sites with a maximum elevation of 1959 m and an average elevation of 1807 m. Highest elevation is observed in the central region of the site, representing a portion of the connecting ridge. About 28% of site C1 show slope below 8° , which is mainly distributed towards the bottom half of this site. Also, it can be observed that the western wall of the ridge is steeper than the eastern

half suggesting that the lower half of the site C1 is an optimal location for landing. The site D has an average slope value of 14° with about 17% of the total area with slope less than 8° and is lowest elevated site out of all with an average elevation of 1105 m and a maximum elevation of 1557 m. The contour lines are more widely spaced in the eastern half of the site D while the western half is more densely covered by the contours indicative of a crater wall. The low slope area, optimal for landing, is localized near the rim portion with relatively good areal coverage compared to site S (Fig. 2b). Site S is located at the most elevated region of the entire Shackleton crater rim and is the second most elevated site among the four landing sites considered (Fig. 2a) with an average elevation of about 1500 m and maximum elevation of 1739 m. The bounding box of site S in Shackleton crater rim has intense slope variations with only a narrow patch of flat area (7.2%) suitable for landing. The maximum slope ($>30^\circ$) observed in the eastern part of the site are also indicated by the closely spaced contours representing Shackleton crater wall.

3.2 Illumination and Earth Visibility

Illumination is one of the most important geotechnical aspects to be considered for any polar mission relying on solar energy for lander and rover operations. Figure 2c shows the LOLA average illumination map of the south polar region, limited to the landing sites considered in this study, and Table S2 lists the maximum average illumination derived using the LOLA average illumination map and modeled average illumination by Gläser et al., (2018) at 2 m elevation. We set a constraint for average illumination as more than 45% and have included percentage area of more than 45% illumination suitable for landing for each site in Table S2. The pixels receiving more than 70% of average illumination are represented in red color in Figure 2c. This map is also very useful for demarcating very low illuminated areas with almost 0% illumination, indicative of local PSRs and also to prepare a trafficability map including the high illuminated areas. Gläser et al., (2018) included illumination conditions at 2 m elevation levels for sites S, C1, and C2. In a similar way, site D has also been simulated and an illumination map is prepared (Fig. S2). All the sites are found to be well illuminated as per the LOLA average illumination map (Fig. 2c) and the extracted values from Gläser et al., (2018) (Table S2), and thus categorized as ‘excellent’ based on the illumination conditions only. We found that about 52% area of the site C1 receives more than 45% illumination (Table S2). The maximum illumination is observed at the higher elevated area of the site C1, resembling ridge-like structure, which also receives longest sun visibility (Gläser et al., 2018). Out of all four sites, site D has only 6% of area of $>45\%$ illumination. Almost three quarters of de-Gerlache rim comes under the average illumination condition, demanding for a pinpoint landing on the rim. The site S consists of about double of the area in comparison to site D with more than 45% illumination.

As described in Section 2, we have also used illumination condition results at a height of 2 m above the ground simulated for a period of 18.6 years obtained by Gläser et al., (2018). Here, we summarized the results considering rover movement on the ground and also at the lander location of height 2 m. As per the simulation results of Gläser et al., (2018), the site S receives maximum average illumination of 85.5% at 2 m above ground examined over a 20-year period. The actual time in sunlight amounts to 89.4% by only

evaluating the binary condition, light or shadow, and neglecting the partial obstruction of the solar disk. The longest period in continuous shadow lasts 66 hours at 2 m height and 221 hours at surface level. According to Gläser et.al., (2018), site C1 records the longest solar visibility being 92.1% for illumination calculated at 2 m above the ground. The maximum average illumination at 2 m height at site C1 is about 88%. The site is in shadow for a total of 268 hours when considering surface illumination conditions and 112 hours at 2 m height illumination level. Site C2 has a maximum average illumination of 79% at 2 m height with 82% solar visibility and the longest time in shadow amounting to 165 hours at 2 m height, which is the longest continuous period found for all the considered sites. At 2 m level, site D receives a maximum illumination of 82.4% mainly confined to the elevated regions as shown in Fig. 2a. Site D is in shadow for 203 hours at surface level and for 151 hours at 2m level.

Along with illumination, Earth visibility is a critical parameter to be evaluated for each landing site as it's important for establishing the communication link to the lander/rover directly from Earth (De Rosa et al., 2012). Earth visibility from each landing site was analyzed with the aid of LOLA average earth visibility map (Mazarico et al., 2011) (Fig. S3), and the extracted average and maximum values are given in Table S3. Table S4 also includes the percentage area of the landing sites with the average duration of Earth visibility greater than 50% (Djachkova et al., 2022). Based on Earth visibility parameter, both the sites C1 and D are categorized as 'excellent' with more than 50% area of the landing sites visible to Earth for direct communication, which will reduce the travel time finding places for establishing relay communication with Earth. The upper half of the connecting ridge of site C1 receives maximum Earth visibility of 58% (Fig. S3). The part of the site D with higher elevation and good solar illumination also offers the maximum Earth visibility. The site S is situated very near to the lunar south pole, offering only 36% of area within the Earth visibility, and thus, categorized as 'poor', whereas the site C2 with about 41% of landing area within the Earth visibility is categorized as 'good'.

3.3 Surface Roughness

The presence of boulders/ejecta materials in already impact rich highlands results in debris that gets widely distributed enhancing the local surface roughness (De Rosa et al., 2012). The roughness of the surface should not be too large otherwise the rover traverse might be a challenge. Areas with a roughness value below 0.4 is preferable for landing as mare regions, which offer smooth landing surfaces exhibits roughness values in the range of 0.4-0.5 (Kreslavsky et al., 2013). Figure 2d shows the topographic roughness map derived using the LOLA DEM. The sites are categorized to 'excellent' and 'good' based on the percentage area with topographic roughness less than 0.4. If a site has roughness values less than 0.4 for more than 10% of its area, the site is categorized as 'excellent', but if less than 10% but more than 5% then the site is categorized as 'good'. The roughness-based ranking of the landing sites is given in Table S4.

All the sites are found to be similar in roughness with average roughness value of 0.5 (Table S4). The sites C1 and C2 are categorized as 'excellent' and the sites S and D as 'good' (Table S4). A total of 15% of the entire area of site C1 is within the limits of roughness constraints (value <0.4), mainly distributed along

the bottom half of the area, which is consistent with the slope map. Roughness increases towards the southern flank of the central ridge of C1. About 12.7% of the total area of the C2 site has a roughness value below 0.4. The maximum roughness values are higher for sites S and D in comparison to sites C1 and C2 due to localized ejecta/boulder deposits, which are probable derivatives from recent impacts (Fig. 5). In such places, the roughness value goes up to 0.8 while on average the site has a roughness value of 0.5. In case of site S, the stipulated roughness values needed for landing and traversing are mainly concentrated along the Shackleton crater rim as a narrow patch that only covers 6.5% of the total area. The crater wall is showing high roughness values, probably due to the distribution of ejected materials from the Shackleton impact event.

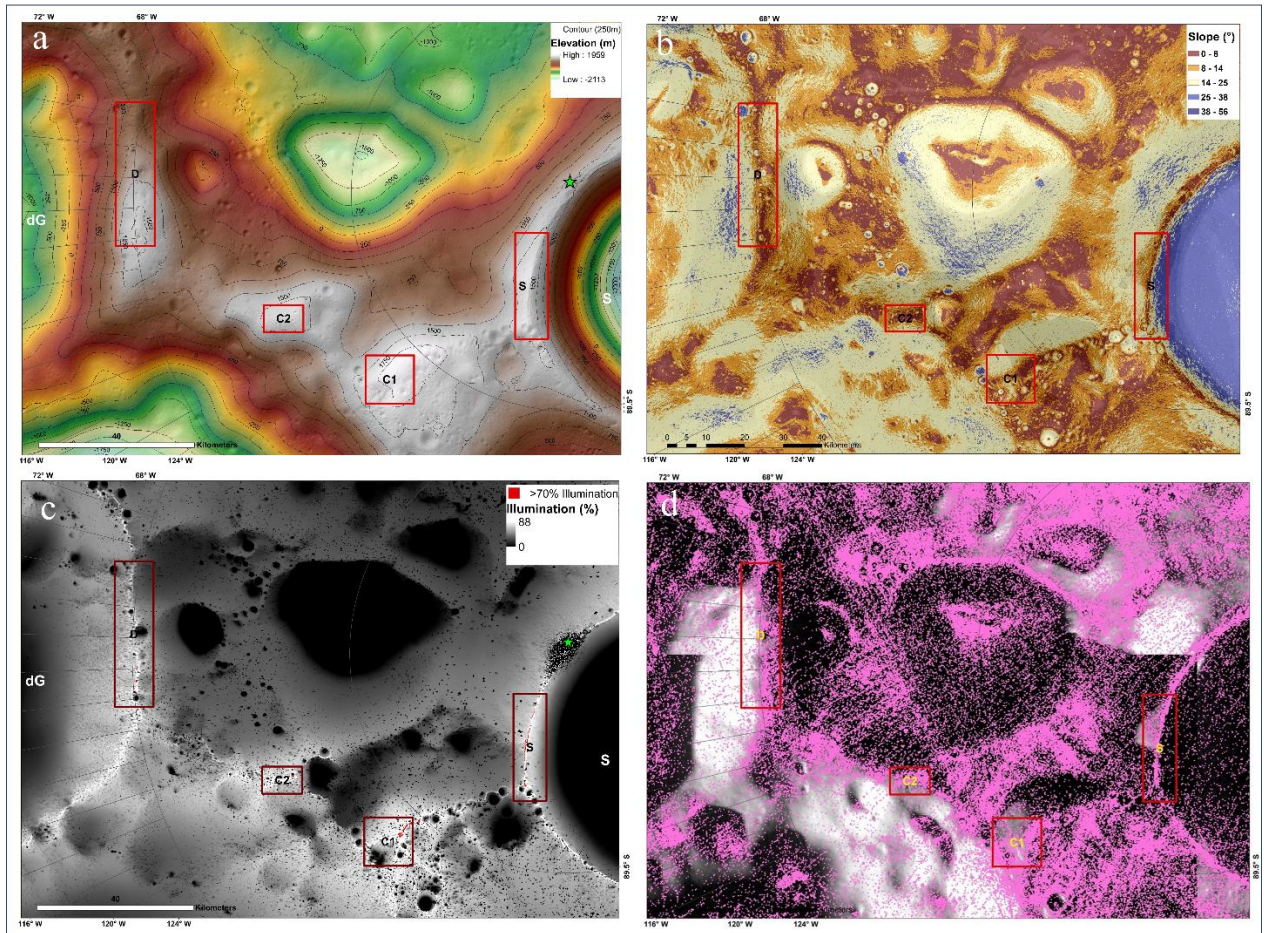


Figure 2. Geotechnical analysis of the landing sites based on LOLA DEM. The red rectangles are the landing area considered. (a) Elevation map color coded in the minimum elevation of -2113 m to 1959 m with 250 m contour interval, added for showing elevation variations within the landing sites. White color represents highly elevated regions whereas low elevated areas are represented in light blue color. All the landing sites are situated on high elevated areas. (b) Slope map of landing sites. Areas suitable for landing and rover operations are indicated in brick red color, and steeper slopes are shown in dark blue. (c) LOLA-based average illumination map of the landing sites. The areas receiving more than 70% illumination are indicated in red color. (d) Surface Roughness map of the study area. Roughness values below 0.4 (indicative of smooth terrain) are highlighted in pink color.

3.4 Trafficability Map

The trafficability of a rover is dependent on slope, illumination and roughness parameters of a landing site. Considering that the four landing sites we selected belong to polar highlands, areas with all three factors coming under the category ‘excellent’ turn out to be relatively small. Instead of looking at slope, illumination and roughness parameters individually, we combined individual evaluation criteria (Tables S1, S2 and S4) by giving proper weights to each parameter as mentioned in Table S5 in order to find out safe regions for landing and rover operations. Considering all weighted parameters (Table S5), we prepared a trafficability map as shown in Figure 3. The green color in this figure indicates areas we found to be ‘excellent’/safe for trafficability within each landing site. Based on the percentage of area available for easy trafficability the sites are categorized as ‘excellent’ if the trafficable area is more than 25% of the overall area or otherwise categorized as ‘good’ (Table S6).

As per the trafficability map, site C2 is the best option for landing and roving as indicated by the widespread distribution of green areas across the site. Site C1 also has a good distribution of trafficable zones except in the north-east and north-west corners. Therefore, sites C1 and C2 are categorized as ‘excellent’. Sites S and D, both located on the crater rims, thus have a limited trafficable area. Compared to site S, site D has a much wider areal distribution of trafficable zone that even extends through the crater wall and can be used for traverse planning to the de-Gerlache crater. The trafficability map for site S (Fig. 3) reveals that the safe zone is limited to a narrow patch of area on the Shackleton rim. The rest of site S is highly challenging for landing and rover operations due to steep slopes and rough terrain.

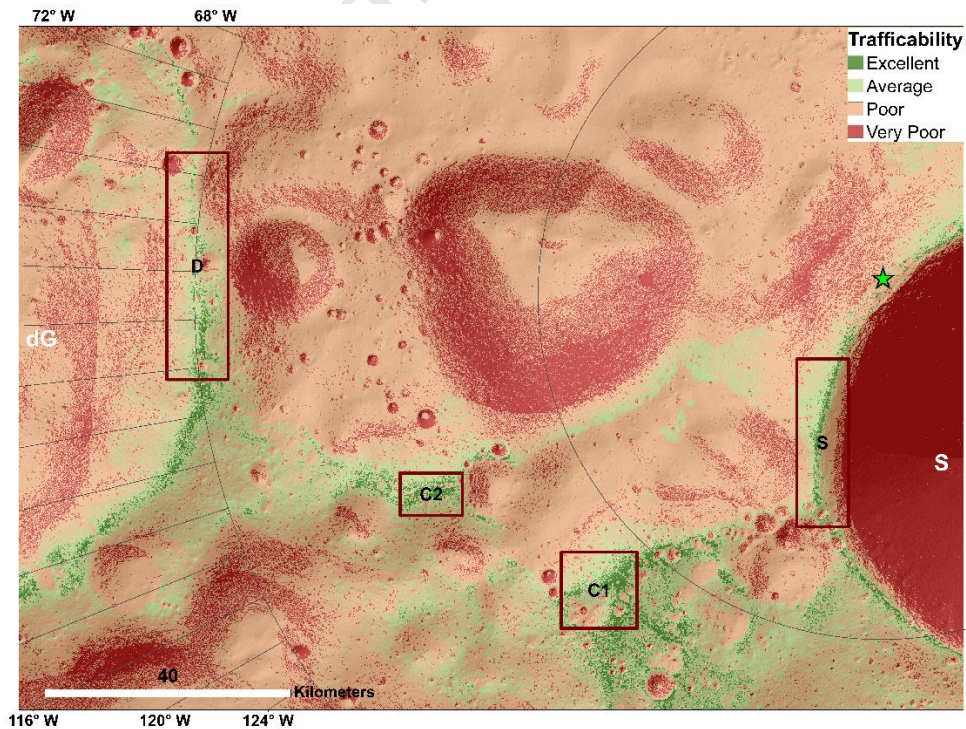


Figure 3. Trafficability map prepared by giving weights to slope, illumination and roughness values (fig 2b-d, Tables S2, S3 and S5). Green areas represent safer regions for landing and traversing while red areas indicate regions with high slope, less illumination and high roughness indicating least favorable conditions for landing and roving.

3.5 Geomorphology

Figure 4 shows the geomorphological map for sites S, C1, C2 and D, which also depicts the mapped boulders. A boulder density map showing the areal occurrence of boulder distribution in each landing site is given in Fig S4. The landing site's geomorphological maps are based on the geomorphic unit classification of Bernhardt et al., (2022). Bernhardt et al., (2022) classified the Shackleton-de Gerlache ridge region into a total of 10 different geomorphic units. More details on each geomorphic unit are mentioned in Bernhardt et al., (2022). We used the same terminology of the units as proposed by Bernhardt et al., (2022), and additionally included the locations of boulders and fresh craters identified using the highest resolution optical images from NAC and OHRC as shown in Figure 4.

As defined by Bernhardt et al. (2022), Cratered Highland Surface (chs) is the most levelled/planar geomorphic unit, which is devoid of any slope disturbances and hence, suitable for landing. Nearby Shackleton crater a similar region is seen, named as Shackleton perched rim (spr), which also offers gentle slope conditions as shown in Figure 2b. Geomorphic units like Intensely slumped surfaces (iss) and Elephant Hide Terrain (eht) need to be avoided during the selection of landing sites as these areas are mainly characterized by steep slope conditions (Bernhardt et al., 2022). Boulders, though important for scientific exploration due to its fresh nature, are a serious threat to rover movement and should be avoided.

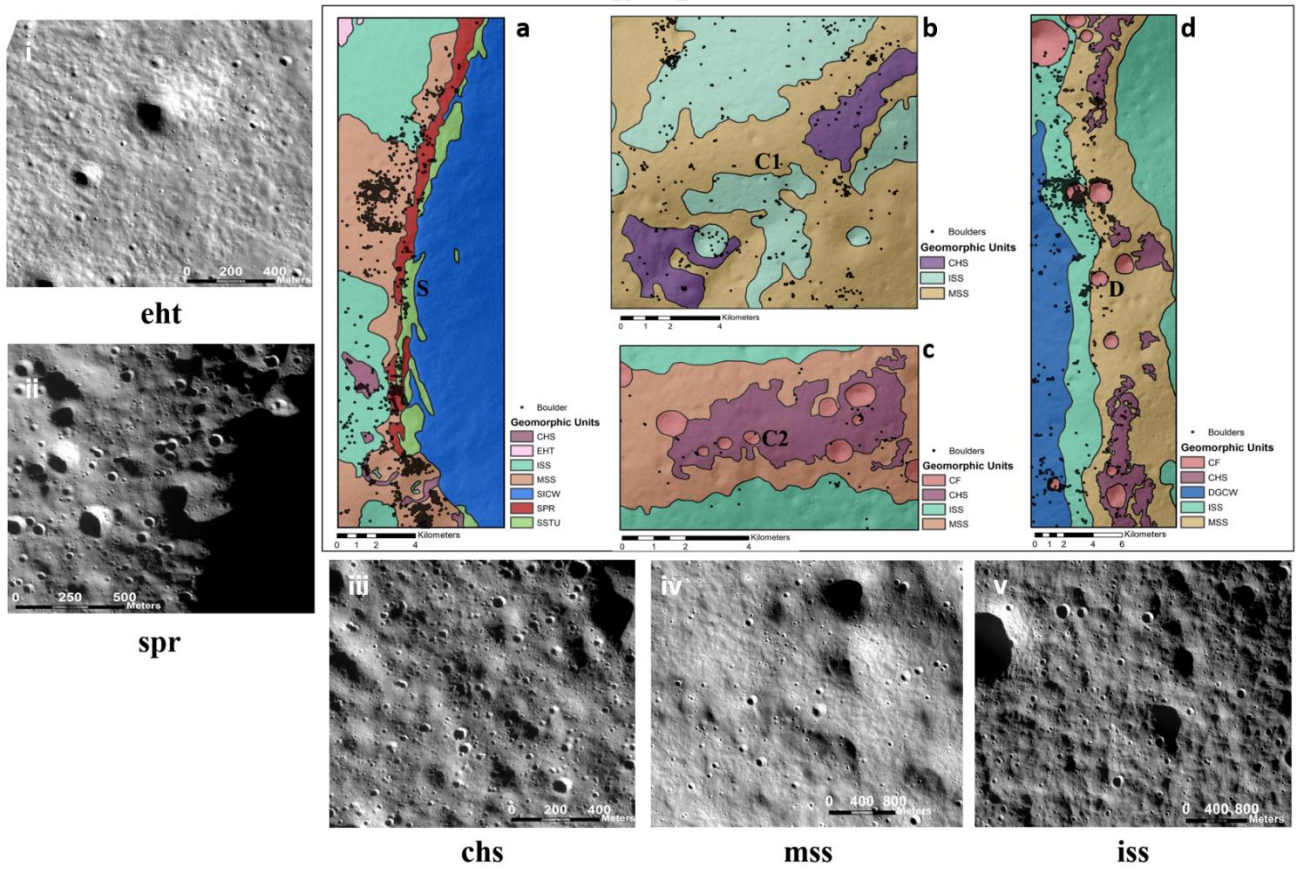


Figure 4. Site-specific geomorphology map of landing sites (a-d) modified after Bernhardt et al., (2022). Figures (i-v) are some examples of geomorphic units are represented using OHRC images from different sites.

Site S (Fig. 4) evaluated as per the Bernhardt et al., (2022) scheme, is composed of seven geomorphic units where the most stable surface conditions for landing and roving are offered by ‘spr’ and ‘chs’ landform units. These results are consistent with the trafficability map in Figure 3 as these two areas belong to the excellent category as indicated in the trafficability map. The Shackleton crater rim has a high density of boulders (Fig S4), with more than 3000 counted and added in Figure 4. This suggests that site S could offer potential sampling sites in the form of boulders but at the same time can also pose challenges for landing and rover operations. A closer view one of the boulder fields mapped using the OHRC images from site S are shown in Figure 5a. Site C1 (Fig. 4) is composed mainly of three geomorphic units; ‘iss’, moderately slumped surface (mss) and ‘chs’ (Bernhardt et al., 2022). Site C1 shows that ‘chs’ is mainly distributed along the top of the ridge while the flanks are represented by ‘mss’ and ‘iss’ landform units that represent an increase in slope and ruggedness (Bernhardt et al., 2022). We found site C2 very similar in geomorphology with exposure of the same units as site C1 (Fig. 4). The site D is diverse in comparison to sites C1 and C2 with many fresh craters and localized ejecta/boulder deposits (Figs. 4 and 5b). A total of four geomorphic units can be identified from site D; chs, mss, iss and de-Gerlache crater wall (‘dgcw’). In contrast to all other three landing sites, site D has the least occurrence of ‘chs’ and maximum occurrence of ‘mss’ unit that covers the center portion of the site surrounded by intensely slumped surface.

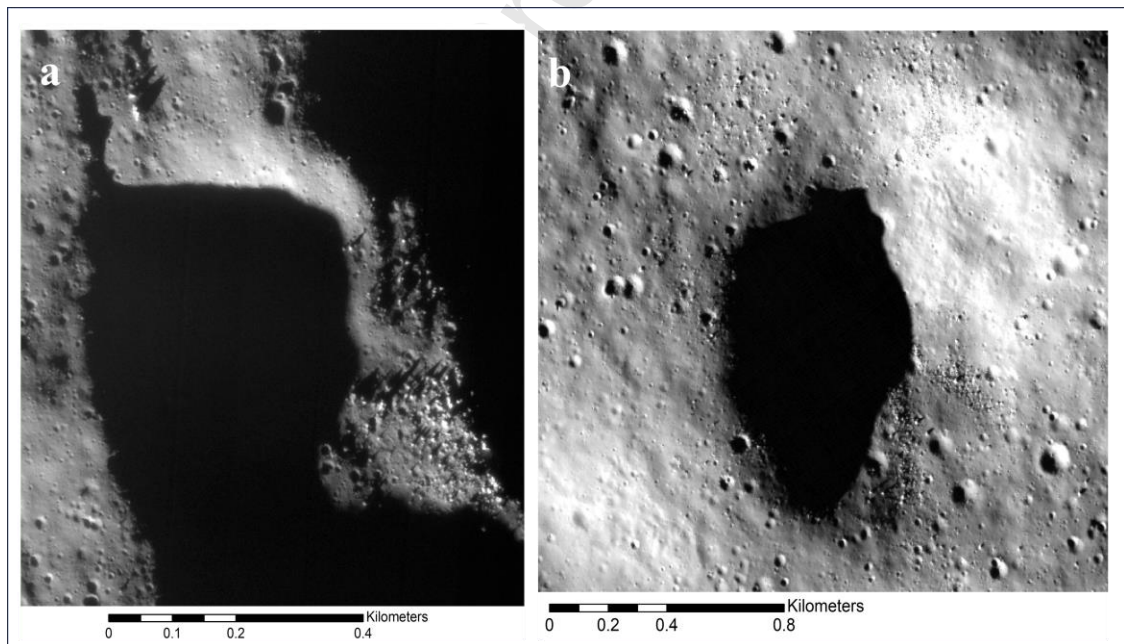


Figure 5(a). Boulder fields in site S taken from OHRC data. (b) Boulder field in site D taken from LROC NAC data

A detailed morphological study of site C1 suggested presence of two lobate scarps (Bernhardt et al., 2022), one located in the PSR (Scarp 1) and the other in the ridge (Scarp 2), which is also marked as the highest elevated area according to the LOLA DEM data (Fig. 6). The character of these two scarps was found to be contradictory as detected from their profiles (Fig. 6b,c). Scarp 1 is around 2 km in length and trends in NW-SE direction. The vergent side of the scarp is in upslope direction with a relief of around 80 m. As the scarp is located in the PSR, visual inspection is not possible and hence, we do not have clarity on further topographic characters and age of the scarp. Scarp 2 is found to be around 1.6 km in length with a relief of

90 m and the vergent side is downslope. Some boulders are visible on both walls of the scarp (Boazmann et al., 2022). Based on the scarp profiles, we are assuming that Scarp-1 is likely to be a lobate thrust fault, indicated by its vergent side direction and other topographic features like relief and steep scarp face (Williams et al., 2013; Sinha et al., 2023). As there are no boulder tracks or associated structures observable due to limitations in visibility, we are not able to confirm whether the scarp is seismically active or not.

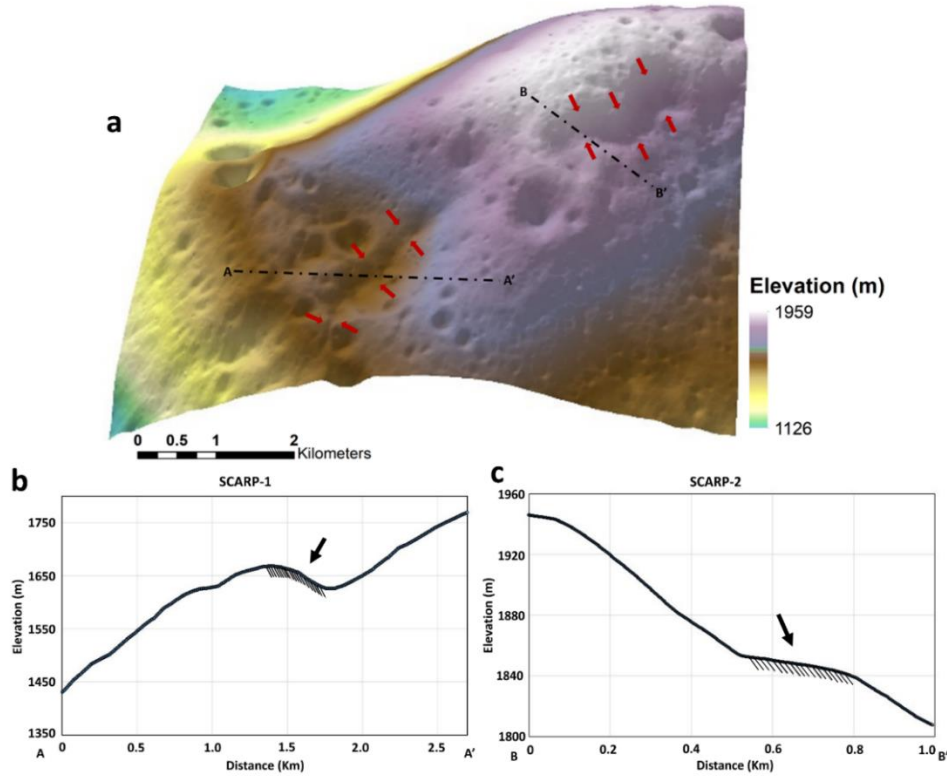


Figure 6(a). 3D color coded image of landing site C1 showing two scarps. (b) Cross-section profile along A-A', drawn across lobate scarp, named as Scarp 1, located at the bottom left of the landing site inside the PSR. (c) The cross section B-B' drawn for lobate scarp (Scarp-2), located at the ridge in the center of the site. The black arrows points to the vergent side of both the scarps.

3.6 Temperature distribution over landing sites

The temperature variations within each site were studied using DLRE maximum, minimum, and average summer and winter bolometric temperature data for finding regions that can host water ice. The annual temperature variation can be used as a proxy to locate PSRs. The temperature variation for landing sites in consideration is shown in Fig. 7. The entire connecting ridge along with de-Gerlache and Shackleton crater rims experiences high temperature during summer reaching around 300 K. The higher temperature is mainly contributed from the direct insolation from the Sun as this region is the highest illuminated region as well as the Earth facing side of the ridge experiences an additional heat contribution from the Earth radiation (Gläser and Gläser., 2019; Gläser et al., 2020). During winter higher temperature is confined to those areas that are highly elevated and highly illuminated. Whereas, there are several regions near to this high temperature and highly illuminated areas that consistently show very low temperature even in different seasons and different vertical scales (Gläser et al., 2020). These regions are devoid of any heat fluxes as they mostly experience

zero illumination, no Earth shine and minimal multiple scattering, and thus, they can serve as potential PSR's (Siegler et al., 2015).

Site specific summer and winter average temperature maps except for site D (not prepared as the data coverage is not uniform) are given in supplementary figs. S5 and S6. For site S, the average temperature is around ~60 K during winter and ~200 K in summer. The maximum temperature from the highly illuminated areas is ~305 K. Site C1 experiences marginal temperature variation with an average annual temperature of 150 K during summer (Fig. 7a) and 115 K during winter (Fig. 7b). The maximum temperature observed is 258 K at the ridge and the minimum temperature is 45 K from the crater situated at the bottom left corner of C1-Site (Fig. S5b). For site C2, summer temperature ranges from 75-247 K (Fig. S5c) and during winter it goes down up to 58-65 K (Fig. S6c). Maximum temperature is experienced in the top portion of the ridge due to high illumination and the minimum temperature is experienced in some small craters within the site. The maximum temperature recorded from site D is 294 K and the minimum temperature is 40 K, which is from a PSR as identified from the PSR map (fig. 7a, b). The sites are evaluated as 'excellent' or 'poor' based on the temperature variation less than 100 K or more than that, respectively (Table S7).

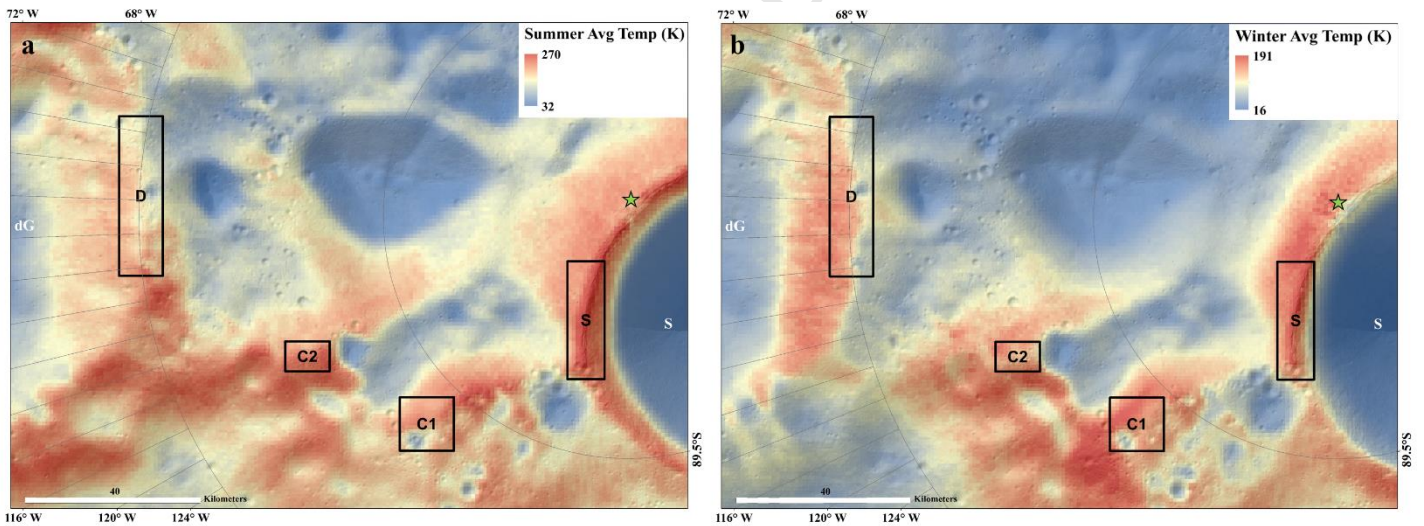


Figure 7. Summer (a) and winter (b) average temperature maps prepared from Diviner data at 240 m resolution. The summer average temperature map ranges from 278 K to 32 K. The winter average temperature map ranges from 190 K to 16 K. There are consistent areas at the Sites C1 and D which show low temperature in both the summer and winter months, indicating PSRs with the possibility of harboring volatiles and water ice. Sites S and C2 show a varied range of temperature for both summer and winter.

3.6.1 Permanently Shadowed Regions (PSRs)

PSR map, following the method described in Section 2, is shown in Figure 8. The weights applied to illumination and temperature in order to find meter-sized PSRs are listed in Table S8. We also included the probability varying from low to high in Figure.8 based on the weights assigned in Table S8. The derived PSR probability map is complimentary to already available PSR maps (Williams et al., 2019; Bernhardt et al., 2022). We report a few meter-sized PSRs (fig 8b) adjacent to landing sites based on the PSR probability map as shown in Figure 8a. The extended shadows cast by a grazing sun angle contribute significantly to the

formation of the depicted PSRs in Figure 8. Specifically, many of these PSRs result from the shadows cast by the de-Gerlache and Shackleton crater rims as well as the connecting ridge, which extend over the adjacent areas. The PSR near the bottom of site-C1 is situated within a crater nested inside another crater, a unique geological arrangement that likely shielded the inner crater from light exposure, fostering its development into a PSR. We cross validated these PSRs using temperature profiles shown in Figure 9. We used the Diviner data, acquired during lunar polar summer, for cross validation. We made sure that the extracted PSR boundary incorporates a minimum of two pixels on the Diviner instrument for gathering the temperature profiles. For larger PSRs, temperature profiles were obtained by calculating the average temperature of all pixels within the PSR boundary. We found that the general trend of the temperature profile is sinusoidal as expected except for PSR-5 and PSR-6 where there is very little variation. The temperature in the region peaks around 3-4 am local time for PSR-5 and PSR-6. PSR-2, south to Shackleton rim, shows the highest maximum temperature of 170 K among the eight PSRs marked in Figure 8b and is one of the biggest PSRs in the vicinity of a landing site.

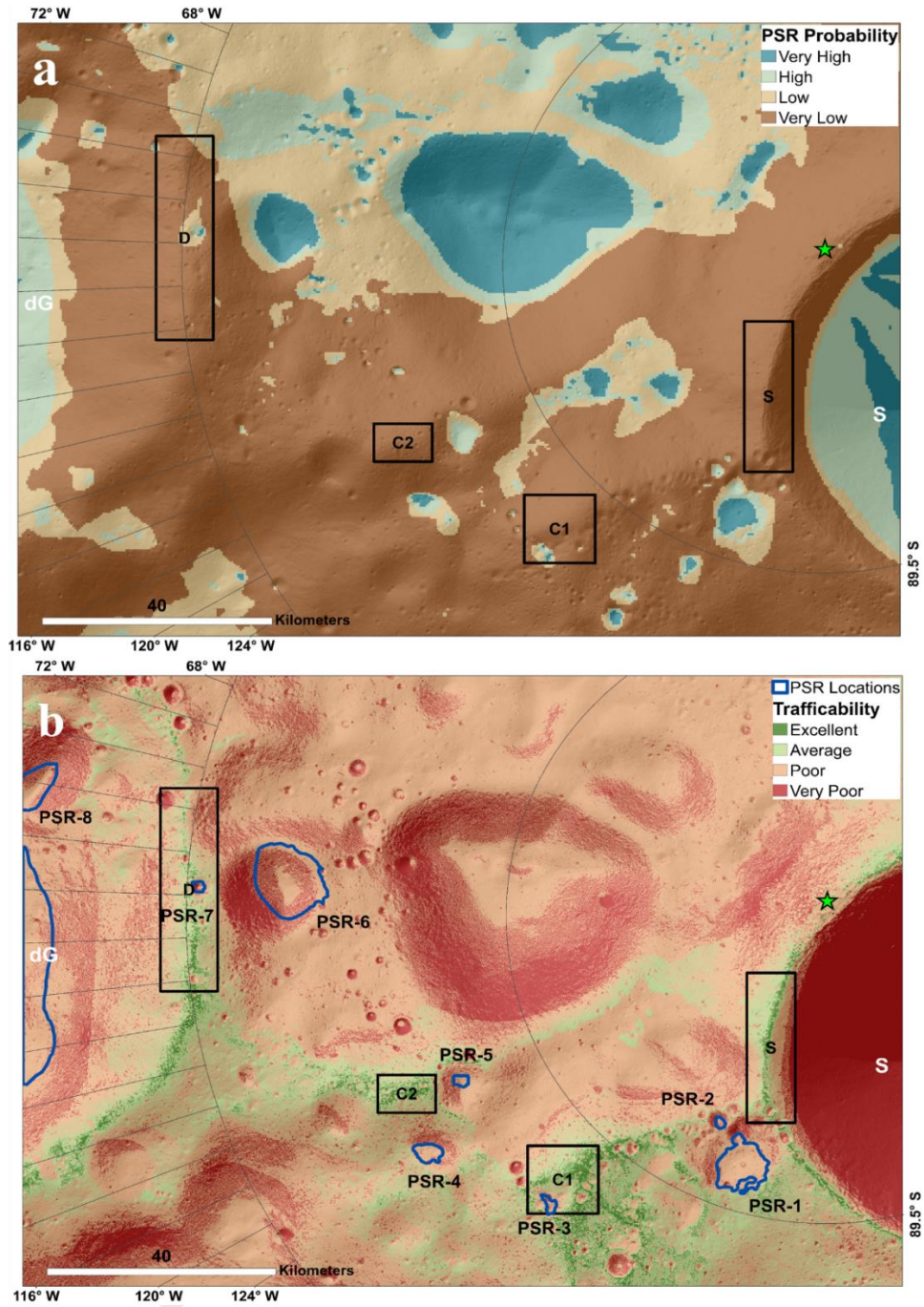


Figure 8: PSR map of landing sites (a) PSR probability map prepared by weighted overlaying of temperature and illumination datasets by giving limits defined in Table S9 for finding regions with lower temperature and illumination. Blue regions are characterized by low temperature and almost zero illumination where it is most likely to find a PSR. The brick red regions represent places where there is lesser probability to find a PSR. (b) Extracted PSR locations around each landing site overlaid on trafficability map for getting an overview on possibilities for building traverse to PSR's.

Ice is considered to be stable at macro and micro PSRs at different depths when it is buried under a layer of insulating regolith in the surrounding areas (Cannon and Britt, 2020). Considering the ice capture (cometary impact, volcanic outgassing, micrometeorite impact combined with solar wind implantation) and retention mechanisms, Cannon and Britt (2020) categorized lunar polar terrain into three types: Terrain

Type-1 represents macro cold traps where ice remains stable at the surface; Terrain Type-2 represents micro cold traps where ice remains stable at a depth of less than 1 m; and Terrain Type-3 represents micro cold traps, with ice remains stable at a depth greater than 1 m. The model proposed by Cannon and Britt (2020) predicted the highest average concentrations of ice consistent at depths of at least 50 cm, even in areas where ice was found to be stable near the surface. Cannon and Britt (2020) inferred that ice stability is not only dependent on the surface temperature but also on the combined effect of impact gardening and surface ice deposition. Figure 10 shows the PSRs found around landing sites overlaid on the polar Terrain Type map of Cannon and Britt (2020). We found that the majority of the PSR's identified through the PSR map belong to Terrain Type-2 category defined by Cannon and Britt (2020) indicating that these PSRs are desirable regions for finding water ice at shallow depth. Out of eight PSRs, three (PSR-1, PSR-5, PSR-6) belong to Terrain Type-1 indicating that these places might hold ice at the surface level, which is also consistent with the results obtained from temperature profiles for the respective regions. These three PSRs are adjacent to sites S, C2, and D as shown in Figure 10. Table S9 lists summer and winter average temperatures along with the distance and Terrain Type of newly detected PSRs. A comparative study with the PSRs detected by Gläser et al., (2018) on the same landing areas is given in the supplementary text.

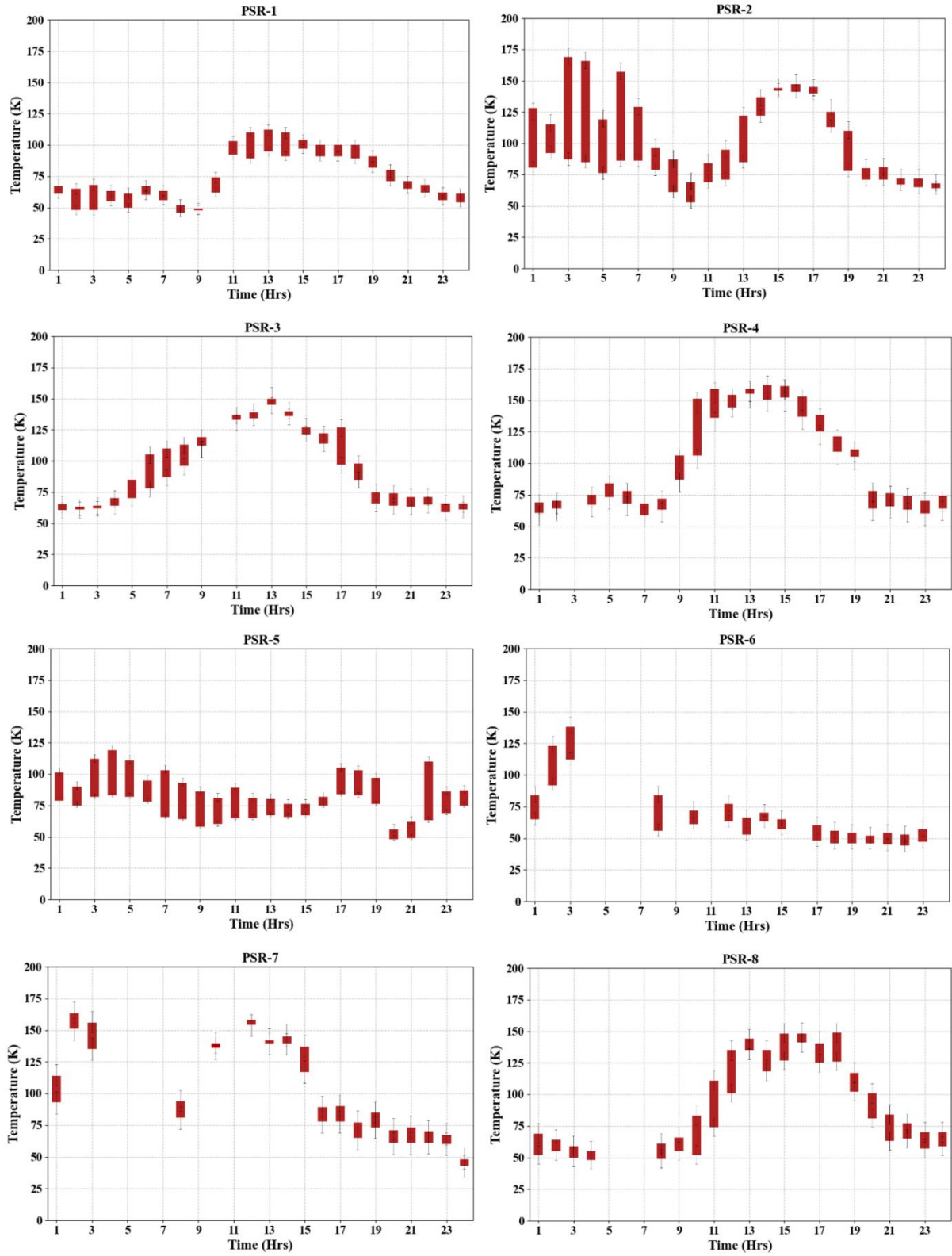


Figure 9. Temperature profiles of extracted PSRs from PSR map on a diurnal scale prepared using Diviner diurnal temperature data

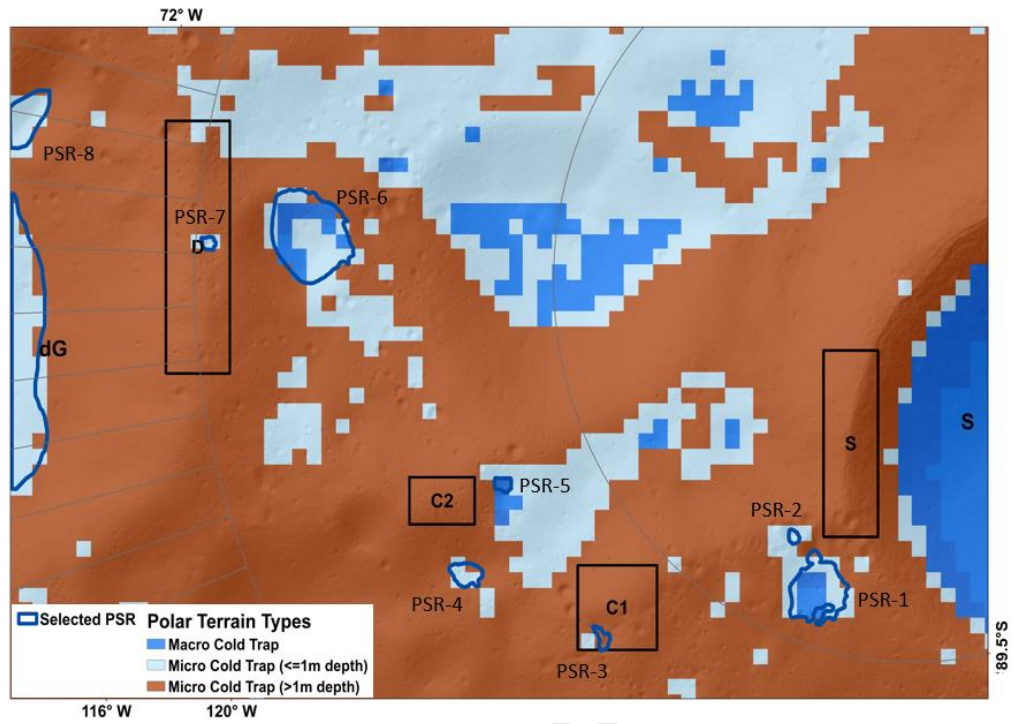


Figure 10. Terrain Type map from Cannon and Britt (2020) with the outlines of PSRs adjacent to landing sites overlaid. PSRs 1, 5, and 6 belong to Terrain Type-1 classification and all remaining PSRs belong to Terrain Type-2 classification given by Cannon and Britt (2020).

3.7 Spectral analysis

We conducted spectral analysis of the landing sites S, C1, C2, and D by extracting M^3 reflectance spectra as explained in the data section. Figure 11 shows the locations of M^3 spectra with absorption features around 1 and/or 2 μm along with the absorption band present around 2.8 μm , which are indicative of OH/H₂O. Hydroxyl (OH⁻) groups associated with a Si/metal cation or molecular water can create stretches of motion. Due to this instability in the molecule, absorption around the 2.8 μm reflectance spectra can be observed (Pieters et al., 2009). We found that the majority of M^3 reflectance spectra from the landing sites show the presence of OH/H₂O band (Fig. 11b, c). The selected sites are dominated by featureless reflectance spectra, representing the shocked plagioclase-bearing lithology. We did not detect the spectral feature corresponding to the Purest Anorthosite (PAN) (Yamamoto et al., 2012). However, a shallow and broad absorption feature around 1.5 μm is detectable from sites C1 and S along with an absorption band around 1 μm . This absorption feature around 1 μm wavelength can be attributed to the presence of pyroxene (<1%) mixed with mature highland soil (Nash and Conel, 1974), and the absorption feature at 1.5 μm wavelength can be generated due to the known artifact of M^3 data because of Order Sorting Filter (OSF) (Green et al., 2011) or the overtone of OH/H₂O (Li et al., 2018) present in these sites. All the reflectance spectra show reddening towards the higher wavelengths suggesting space weathering, a dominant process in this region (Pieters and Noble, 2016; Sim et al., 2017). The absorption band at visible range and around 0.85 μm was detected in the reflectance spectra near the proposed landing sites, which could be due to the presence of hematite (Fig. 11d, e). Hematite in the context of the Moon was first identified from Apollo 14 samples, which were initially attributed as a result of contamination from extra-lunar hydration (Agrell et al., 1972) or changes in redox

states, which result from equilibrium cooling in the presence of a plausible lunar fluid phase (Williams and Gibson, 1972). Recently, the widespread distribution of hematite over lunar poles with much more concentration on the near side of the Moon has been reported by Li et al., (2020) using the M³ datasets. Hematite is a common oxidized mineral on Earth, forming under highly reducing conditions prevailing on the Moon, making it a controversial yet interesting topic of exploration. The M³ pixel locations corresponding to reported hematite exposures (Li et al., 2020) are marked in Fig. 11a for future south polar exploration in order to precisely identify and quantify hematite. As shown in Fig. 11a, site D and site C1 cover the clustered distribution of hematite while site S and site C2 show scattered exposures of hematite.

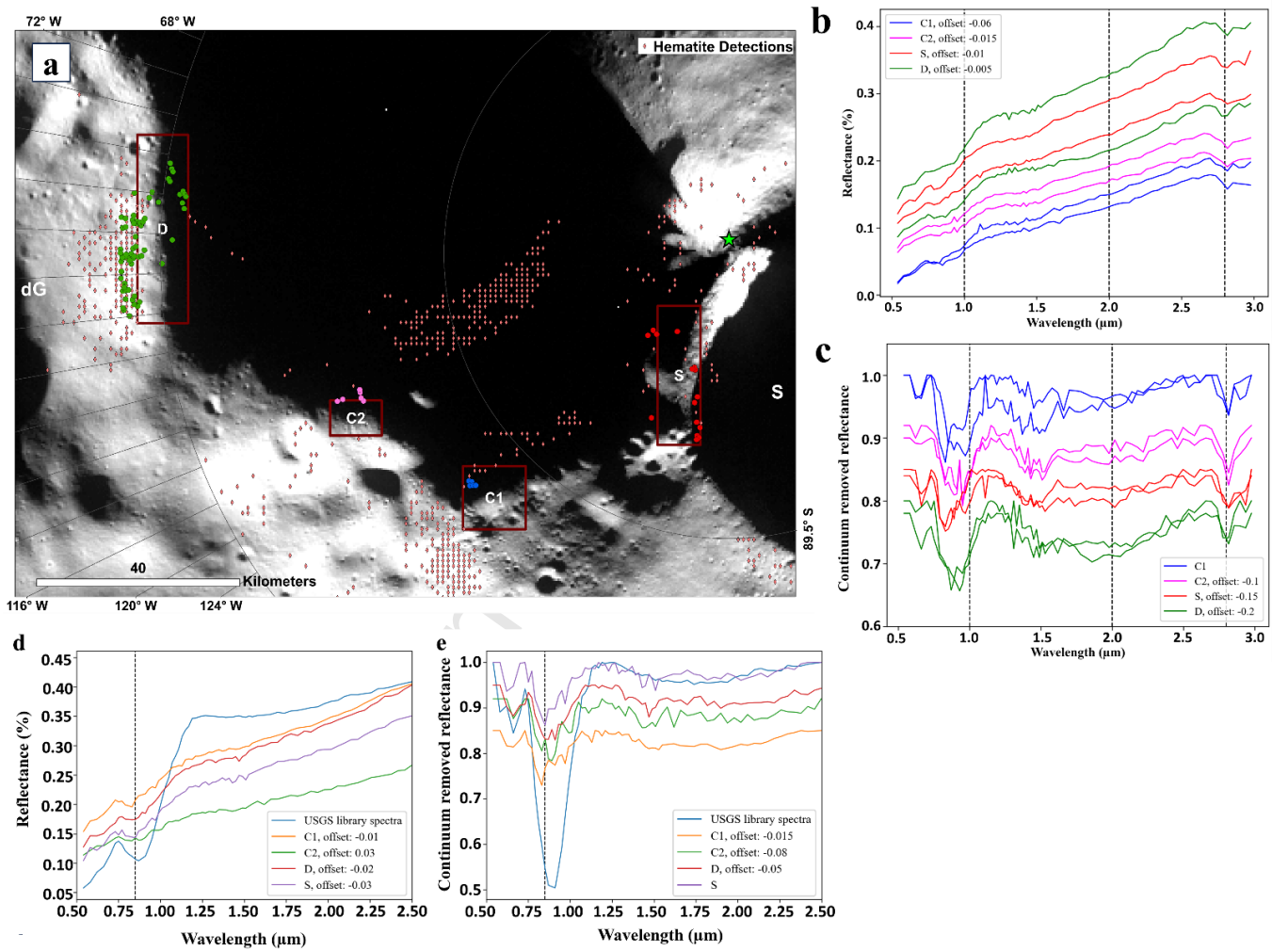


Figure 11. Spectral analysis of landing sites (a) Representative spectra from color coded pixel locations of M³ spectra containing absorption features around 1 and 2 μm along with 2.8 μm absorption corresponding to OH/H₂O. The base image is LROC-WAC with hematite detection points after Li et al., (2020). The spectra are colour coded for each site (b) representative reflectance spectra from each site (c) continuum removed spectra with offset applied for clarity. The dashed black lines at 1, 2 and 2.8 μm are for reference. The detections are mainly scattered except for site-C1 where it appears as cluster (indicated in blue color) just above the PSR detected using PSR map. Site-D holds the maximum no. of OH/H₂O detections, which is also distributed to towards the crater wall (d) Some representative spectra with suspected hematite absorption gathered from each site along with the hematite spectrum collected from USGS spectral library are plotted

(e) with their continuum removed counterparts, which are showing prominent absorptions around 0.6 and 0.85 μm . The dashed line at 0.8 μm is given for reference.

4 DISCUSSION

The landing sites S, C1, C2 and D considered in this work are important targets for any south polar exploration mission planned. This work is mainly focused on upcoming the ISRO-JAXA mission (Saiki et al., 2021). Our attempt is to prioritize the four landing sites considered for ISRO-JAXA and Artemis missions (Saiki et al., 2021; Bernhardt et al., 2022) planned to be launched in the next few years. The prioritization is based on the technical and long-term scientific exploration assessments. Table 2 summarizes the main parameters considered for the ranking of the landing sites. The site that came out excellent for the maximum number of times while evaluating the geotechnical and scientific factors is given a rank of 1. The lowest rank is given to those sites which fails to meet the constraints mentioned for each parameter.

Table 2 Summary and ranking of each landing site on the basis of technical assessment and expected scientific outcomes.

Site	Avg. Elevation (m)	Avg. Slope (°)	Max. Avg Illumina-tion (%)	Max Avg Illumina-tion at 2m level (%)	Avg. Earth Visibility (%)	Trafficable area (%)	Avg. Temp. (K)	Age	No. of PSR	Exploration Targets other than PSR's	Rank
S	1500	20	87	85.5	29	7	130	Eratosthenian	2	PAN Geological Boundary	4
C1	1807	11.5	88	88	30	28	132	Pre-Nectarian	1	SPA Basin ejecta, Seismic studies in the lobate scarp, Hematite	1
C2	1594	10.6	79	78.1	31	30	153	Pre-Nectarian	2	SPA Basin ejecta	2
D	1105	14	78	80	44	5	167	Nectarian	3	Geological Boundary, Hematite, de-Gerlache crater (Potential cold trap)	3

As listed in Table 2, the assessment shows that each landing site is having its own challenges of landing and exploration. We found sites C1 and C2 are comparable from trafficability point of view but the site C1 is scientifically more interesting with the presence of scarps (Fig. 6) and a PSR in the vicinity. Site C1 appears an excellent choice for landing (Table 2) being situated at the ridge connecting de-Gerlache and Shackleton

craters. Therefore, site C1 is given first priority as a landing site for a south pole mission. In a similar way, sites S and D are found to be comparable for landing and rover exploration based on the safe landing conditions. Site S is found scientifically very interesting but demands for a precise landing considering its geotechnical evaluation (Table 2). Site S is found to be the narrowest stretch for landing and exploration among all. The boulders within site S may pose a threat to the rover operations while planning to traverse to fresh craters and scattered ejecta deposits. The average slope for site S is about 20° . Site D is similar to Site S based on expected scientific outcomes and exploration of PSR and also offers possibilities of traverse with a rover. The average slope of site D is about 14° slope. Based on these outcomes, site D is prioritized over site S. Here, we elaborate further on site D and site C1, which we found can be optimized and explored in detail through a lander/rover mission for gaining maximum scientific outcomes.

The site D shows variations in local mineralogy with a few clusters of newly detected hematite deposits. The presence of micro PSRs in addition to de-Gerlache PSR and the geological boundary between Pre-Nectarian and Nectarian-type terrain can be explored using a rover if site D is considered for landing. The slope breaks inside de-Gerlache crater wall region can be used to put a traverse from the landing site to the interior of de-Gerlache crater. The interior of de-Gerlache crater act as cold trap (Flahaut et al., 2020) with temperature as low as 50 K can even hold CO_2 in ice form (Berezhnoy et al., 2012; Cannon and Britt, 2020). The ice accumulation probability is high at de-Gerlache PSR in comparison to Shackleton PSR considering the geological time period of formation of these two craters as well as their temperature distribution (Table 2). However, this site requires a precise landing mechanism considering its location on the crater rim of de-Gerlache crater with only narrow region feasible for landing in a similar way as site S. The site D showed abundant boulders (~ 150 easily detectable in OHRC and NAC images) that could be hazardous for rover operations. As boulders are also important targets for exploring fresh local materials, we prepared a traversability map of site D that can serve as a reference prior to landing for rover path planning. Figure 12 includes the points of scientific interest that can be considered for detailed sampling using a suite of instruments for in-situ exploration. The traverse follows the results obtained from trafficability map, which ensure stable slope, with more than 50% illumination and less than 0.5 roughness. The traverse is extended to reach up to de-Gerlache crater floor following the slope breaks, which is not exceeding 20° anywhere. One of the scientific interests for any south polar landing mission is to find out local stratigraphy and sample materials from different depth layers. The ejecta thickness for a particular area can be calculated using an empirical relationship involving distance and diameter of both simple and complex craters. The thickness of the ejecta will be higher near the crater rim and have an inverse relationship with distance (Kring et al., 1995). In this regard, we calculated the ejecta thickness at site D from the surrounding craters. The distance of site D from the center of the de-Gerlache crater is ~ 16 km. We selected nearby craters like Shackleton (~ 39 km apart), Henson (~ 30 km apart) and Spudis (~ 15 km apart) assuming that ejecta from all these craters might have distributed uniformly over the landing site. Out of these craters, Henson and Spudis are the

oldest craters (pre-Nectarian) followed by de-Gerlache (Nectarian) and Shackleton (Eratosthenian) (Kumari et al., 2022). Hence, the ejecta deposits in site D should also follow the same sequence suggesting that the ejected material from Shackleton should be on the top. The ejecta thickness is calculated using following formula (Kring, 1995).

$$\delta = 0.04 R_s [r/R_s]^{-3.0 \pm 0.5}$$

$$\delta = 0.14 R_c [r/R_c]^{-3.0 \pm 0.5}$$

where, δ is the ejecta thickness, r is the distance from point of impact, R_s is the radius of the simple crater and R_c is the radius of the complex crater (in m).

From above equation, we estimate ~8 m thick ejecta at de-Gerlache contributed by Shackleton impact event that overlaid the de-Gerlache impact ejecta of ~200 m thickness. The contribution from Spudis and Henson impact events is ~20 m and ~82 m, respectively that will be situated at greater depths (>200 m). Hence, small craters with shallow depths (<8 m) might have Shackleton ejecta but the craters with depth more than ~200 m might have de-Gerlache ejecta. The craters with small to larger crater diameter will be interesting to explore through rover for understanding local stratigraphy. We have marked several such craters in Figure 12 that can be considered as sampling sites. Supplementary Table S. 10 lists depth and diameter of these craters.

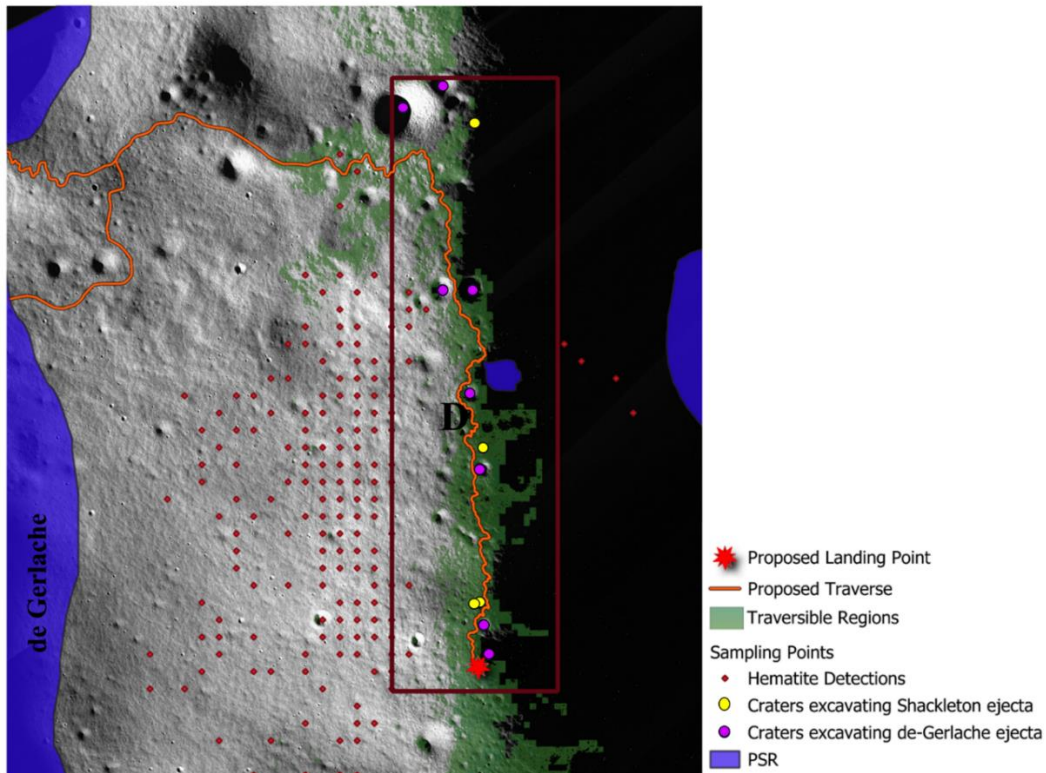


Figure 12. Traverse map for site D. Base image is LROC NAC.

Another important outcome of this work is the importance of site C1, situated on the connecting ridge of de-Gerlache and Shackleton craters. This ridge is most likely to be formed from SPA impact and have witnessed de-Gerlache, Shackleton impact events. The site can be explored to get signatures of all these impact events from three different geological time periods (Table 2) that should be preserved here. The site C1 is the best among all considering the maximum average illumination at 2 m above ground of ~88% and the longest solar visibility of ~92% (Table 2) (Gläser et al., 2018), making this site the most favorable considering lander height of about 2 m. The traverse area and landing area within site C1 is the highest among all considered sites, relaxing the need of precise landing as is the case for sites D and S. PSR at the site C1 is in close proximity and easy to explore through a medium size rover. PSR is found to be a prominent location of ice accumulation as per the temperature range (maximum of 150 K and minimum of 60 K) and Terrain Type-2 (Table 2). Fig. 13 shows contrast enhanced OHRC image corresponding to PSR overlaid on the unworked OHRC data covering site C1.

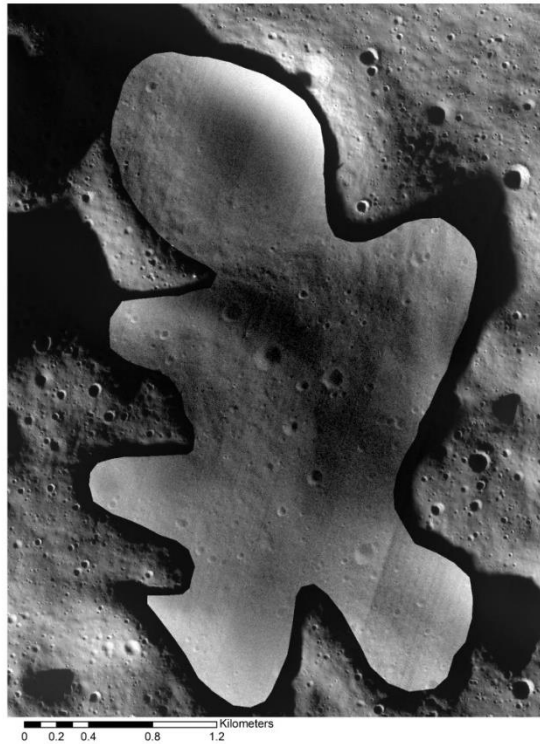


Figure 13. A contrast enhanced OHRC image of C1 PSR showing the interior of the PSR overlaid on the original OHRC image showing the location of PSR. The location of PSR with respect to site C1 is given in Fig.14.

We calculate ejecta thickness of landing site C1 in a similar way as site D. For calculating the ejecta thickness for site-C1, Shackleton (~21 km apart), de-Gerlache (~36.5 km), Spudis (~14 km), Henson (~26 km), and Sverdrup (~34 km) impact events are considered. The ejecta deposition order is considered pre-Nectarian to Eratosthenian. We found that the ejecta deposits from Shackleton impact is ~48 m, underlined by ejecta deposits from Sverdrup of ~20 m thickness, de-Gerlache of ~16 m thickness and Spudis and Henson having ejecta deposits of ~23 m and ~132 m, respectively. Some craters excavating de-Gerlache and

Shackleton impact ejecta are identified at the site C1 in a similar way as for site D. The details on location as well as depth and diameter of these craters are given in Table S.11. Figure 14 shows a proposed traverse considering scientifically important sampling sites.

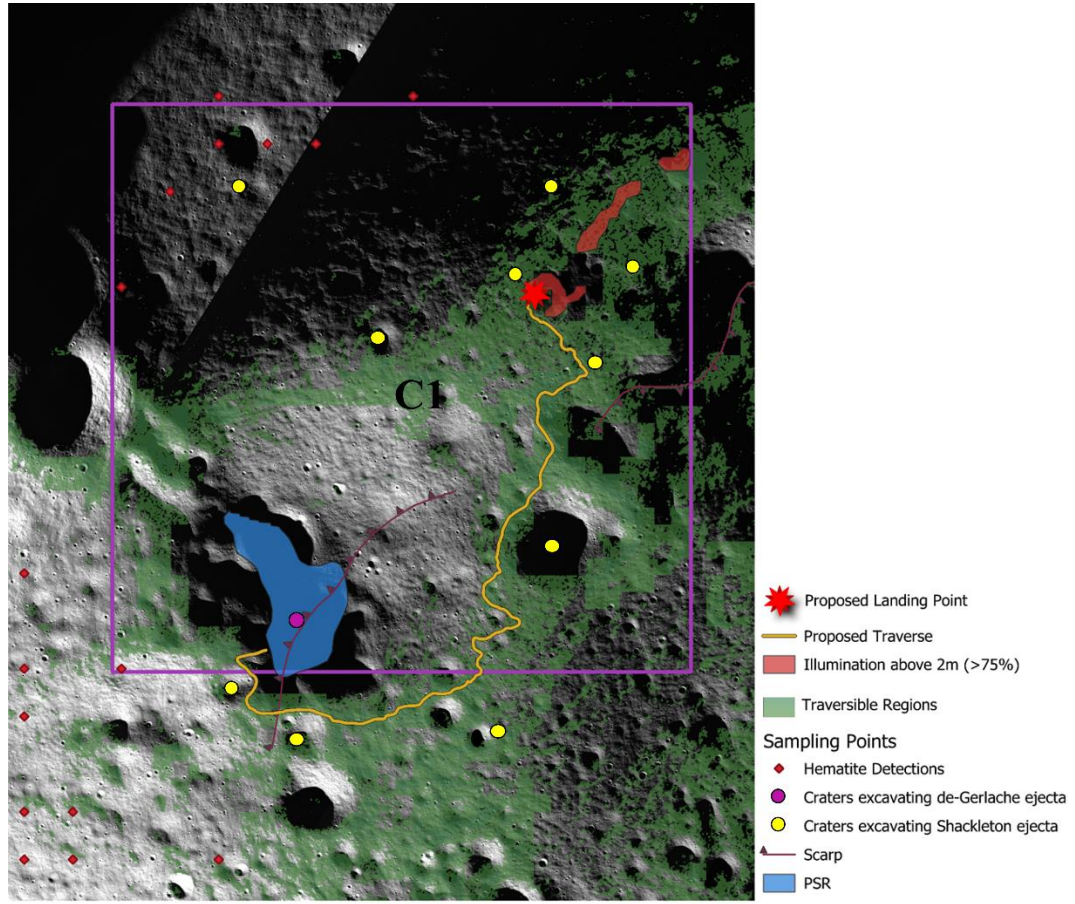


Figure 14. Traverse map for site C1 including sampling points. Base image is LROC NAC.

5 CONCLUSIONS

Considering upcoming ISRO-JAXA mission to the lunar south pole, we investigated four potential landing sites near the lunar south pole and evaluated their potential in terms of geotechnical constraints for landing/rover operations and expected scientific outcomes. The sites S, C1, C2, and D, situated between de-Gerlache and Shackleton craters, are partially under the shortlisted targets of Artemis mission also. We adopted multi-mission, multi-wavelength analysis in order to prioritize the selected sites based on their technical feasibility, proximity to a PSR and expected scientific outcomes (Table 2). The detailed analysis of sites S, C1, C2, and D suggest that site C1 is the best among all sites considering slope, illumination, landing area, and roughness conditions needed for a safe landing and rover operations. Aided by its high elevation, site C1 can offer a constant line of sight with rover as the landing point is marked at the highest elevated location. Its proximity to a micro PSR, its location on connecting ridge between de-Gerlache and Shackleton, presence of scarps, and OH/H₂O-rich mineralogy with hematite deposits in 500 m of vicinity advocate this site to be scientifically enriched. This site receives the maximum solar illumination and visibility to Earth, a requirement for continuous operation during the lunar days. The site C1 must have

received ejecta materials from both de-Gerlache and Shackleton impact events suggesting that exploration around craters with tens to hundreds of meters in diameter will lead to building up local stratigraphy, an important tool for understanding lunar polar geology. The integrated approach used for characterizing the landing sites suggests that site C1 is an ideal landing site for mission that aim to explore volatiles within a short span of time without long traverses. We defined a landing spot within the landing area considered based on the technical assessment of the site (Table 2). The landing spot considered (Fig. 14) is comparatively flat with a slope of less than 8° and illumination of more than 60% on the ground. The nearest micro PSR is situated about 1 km from the landing spot (Fig. 14). This newly reported PSR's average temperature is found to be below 90 K throughout the lunar cycle indicating a stable environment for the presence of water ice at shallow subsurface. Based on PSR location, craters of different diameters, and hematite and OH/H₂O rich mineralogy, a tentative traverse path has been proposed from the landing spot to the adjacent PSR of length ~ 1.5 km. This traverse also includes two scraps that will be interesting to explore with a rover.

The second best option for landing and for scientific exploration is found to be site D, in proximity to de-Gerlache crater, which is a PSR like Shackleton crater. The ejecta deposits from nearby impact events suggest that mineralogically site D is the most interesting with a possibility of detection of PAN and orthopyroxene-rich mineralogy. The sampling of this site might help in understanding SPA impact event (Spudis et al., 2008). Site D is technically easier to explore in comparison to site S, which is located on the rim of the Shackleton crater. Except this condition, the scientific importance of site D and site S is the same. A traverse plan can be formulated (Fig. 13) to explore de-Gerlache PSR that will be very challenging in the case of exploring Shackleton PSR from site S due to steep slopes at the crater wall. We found that site D is suitable for missions planned with long-term exploration duration with several sampling stops.

Site C2 is found to be equally feasible considering the technical aspects for landing as site C1 but this site does not add any additional scientific advantage with respect to the other three sites selected for a comparative analysis. Two PSRs are located around site C2 but are about 3 km away from the landing site. Site C2 is the smallest in terms of area among the four sites considered. Based on the scientific constraints, site S is the best location due to its proximity to Shackleton crater with evidence of water ice exposures. The ejecta material deposits around this site due to its Eratosthenian age will be important for establishing a link between volatile transport with local scale morphology and mineralogy. The site is situated at a high elevation that provides average illumination at surface level of 87% but the trafficability from this high elevation area to PSR is challenging due to steep slopes all around the landing site (Table 2). Site S is considered one of the most important landing sites (Bernhardt et al., 2022; Hoshino et al., 2020) but this work suggests that sites D and C1 provide better exploration options without much compromise to scientific objectives and comes under present technical capabilities of small-size rovers.

This work provides alternative options to Shackleton crater landing site for future south pole exploration landing missions. All the sites considered here are not too far from Shackleton crater but avoid extreme topography, are well illuminated, and most importantly is situated in the vicinity of a PSR that is accessible and capable of providing answers to some of the open questions related to the nature of volatiles, linkage to local geology and interaction processes. Understanding water resources and interaction and accumulation processes will pave the way for sustained human exploration on the Moon.

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Data Availability

All the data used in the present study are freely available and can be accessed from the following websites. LRO NAC and WAC mosaics used for the present study are available at <https://www.lroc.asu.edu/>. LOLA based polar illumination maps are available at <https://pgda.gsfc.nasa.gov/products/69>. Ch-2 OHRC data used for this study can be downloaded from <https://pradan.issdc.gov.in/ch2/>. LOLA DEM data is available at <https://pgda.gsfc.nasa.gov/products/81>. M³ data is available at <https://pds-imaging.jpl.nasa.gov/volumes/m3.html>. Hourly temperature maps of the south polar region are available at http://luna1.diviner.ucla.edu/~jpierre/diviner/level4_polar/hourly_maps/south/. Diviner lunar south pole summer and winter average temperature maps can be downloaded from https://luna1.diviner.ucla.edu/~jpierre/diviner/level4_polar/additional_maps/. Polar Terrain Type maps were downloaded from <https://kevincannon.rocks/lunarmining/>.

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Supplementary Text

We extracted Diviner diurnal temperature data for the PSRs already studied by Gläser et al., (2018). The PSR-1 in Figs. 6 and 8 is a common detection in this study and Gläser et al., (2018) (mentioned as PSR/S0 in his study) hence we excluded that as it is already discussed in the main text. For all other PSRs detected by Gläser et al., (2018), we plotted Diviner diurnal temperature profiles (Fig. S7) and found that these PSRs cannot preserve ice for a longer period of time as they are located adjacent to the highest illuminated regions experiences higher temperature variations (as evident from illumination and temperature maps). The crater mentioned are also small-scale ones having depths only to several meters hence likely to sustain the same temperature as that of outside the crater. Ice can be stable in these locations at a depth more than 3m.

It is seen that PSR/ S1 is having a maximum temperature around 280 K (Peak hour 7 pm) and for almost 15hrs the PSR is exposed to a temperature above 200 K. Profile shows a sinusoidal pattern with double maxima occurring at 8 am (240 K) and 7 pm (280 K) separated by a lower temperature point at 1 pm (100 K). In the case of PSR/C1-0, the maximum temperature observed is to be near 250 K at 5 AM. The lowest temperature of 90 K is attained at 12 PM noon. The profile overall shows a declining trend with higher temperatures during midnight hours and lower temperatures during noon. The temperature profile from PSR/C1-1 is not showing much variation and is maintaining a temperature range of 160 K-400 K throughout the profile except for a lower temperature condition (80 K-170 K) occurring around 11 AM local time. The temperature fluctuation is so intense hence, the probability of finding ice in this particular location will be low. Apart from other PSRs discussed before, the temperature profile of PSR/C2-0 and PSR/C2-1 shows a lower temperature of around 70 K during midnight. Temperature varies roughly in the 140-200 K range for PSR C2-0 and the highest temperature of 230 K is attained at 5 am. The temperature of range PSR/C2-1 is slightly higher which is around 170-240 K with the highest values marked during 3 pm-7 pm. The temperature rise during evening hours is consistent with all the PSR's but in variable amounts. As the temperature is going beyond 250 K and staying longer periods above 200 K as well as having negligible depth to get masked by the shadow, PSR/S-1 and PSR/C1-1 are less likely to hold ice. The temperature of PSR/C1-0 and PSR's of site C2 are still high but as they are not exposed to higher temperatures for a longer period, there might be a possibility of getting water ice at greater depth.

Supplementary Tables:**Table S1:** Landing sites evaluation on the basis of the slope. The percentage of area with a slope less than 8° which will be available for landing and the percentage of area with a slope less than 14° available for rover movement are listed. The evaluation result is based on the description given in Section 2.

Site	Average Slope (°)	% of area with slope <8°	% of area with slope <14°	Evaluation
S	20	7.2	30	Poor
C1	11.5	28	66	Excellent
C2	10.6	30	76	Excellent
D	14	17	54	Poor

Table S2: Landing sites evaluation on the basis of the illumination. The table lists the values extracted for landing sites from the LOLA illumination map and based on the simulated illumination conditions of Gläser et al., (2018)

Site	Max. Avg Illumination (%) (LOLA)	% of area having more than 45% illumination	Max time in shadow (hrs) at surface level (Gläser et al., 2018)	Max. Avg illumination at 2 m elevation (%) (Gläser et al., 2018)	Max time in shadow (hrs) at 2 m above ground (Gläser et al., 2018)	Evaluation
S	87	12.5	225	85.5	66	Excellent
C1	88	52	268	88	112	Excellent
C2	79	35	165	78.1	165	Excellent
D	78	6	203	82.4	151	Excellent

Table S3: Earth visibility values for each landing site and its corresponding evaluation results.

Site	Average Earth Visibility	Maximum Earth Visibility	Area with >50% earth visibility (%)	Evaluation
S	0.29	0.56	35.7	Poor
C1	0.3	0.58	51.6	Excellent
C2	0.31	0.58	40.87	Good
D	0.44	0.59	54	Excellent

Table S4: Evaluation results for the roughness of landing sites. On the basis of the percentage of areas exhibiting low roughness values, the landing sites are ranked.

Site	Avg. Roughness	% of area with roughness < 0.4	Evaluation results
S	0.5	6.5	Poor

C1	0.5	15	Excellent
C2	0.5	12.7	Excellent
D	0.5	7.6	Poor

Table S5: Limits applied to slope, illumination and roughness datasets for trafficability analysis.

Factor	Classification	Weightage at scale of 4 with 4 being the best
Slope	0-8°	4
	8-14°	3
	14-22°	2
	>22°	1
Illumination	>45%	4
	45-35%	3
	35-25%	2
	<25%	1
Roughness	<0.4	4
	0.4-0.5	3
	0.5-0.7	2
	>0.7	1

Table S6: Evaluation based on the percentage of trafficable areas available for each site.

Site	% of trafficable area	Evaluation results
S	7	Good
C1	28	Excellent
C2	30	Excellent
D	5	Good

Table S7: Evaluation results on the basis of temperature variation. Site C1 is ranked high as it shows minimum temperature variation from summer to winter and in other sites the temperature variation goes beyond 100K.

Sites	Summer Avg Temp (K)	Winter Avg Temp (K)	Variation (K)	Evaluation
S	200	60	±140	Poor
C1	150	115	±30	Excellent
C2	240	60	±180	Poor
D	290	40	±250	Poor

Table S8: Limits applied to illumination and temperature datasets for PSR analysis.

Factor	Classes	Weightage at scale of 4 with 4 being the best
Temperature	<100K	4
	100-120K	3
	120-150K	2
	>150K	1
Illumination	0-2%	4
	2-5%	3
	5-10%	2
	>10%	1

Table S9: Evaluation results based on PSR's. The distance of the landing site is calculated from the center of each landing site. Accessibility is expressed in terms of trafficability to each PSR from the landing site. As all PSR has enough potential, priority is given more to the shortest distance and accessibility.

Site	PSR's Identified	Summer Avg Temp (K)	Winter Avg temp (K)	Terrain Type (Cannon, 2020)	Distance to PSR from the landing site (km)
S	PSR-1	78	58	TT-1	6
	PSR-2	103	64	TT-2	5
C1	PSR-3	100	86	TT-2	1.5
C2	PSR-4	119	96	TT-2	3
	PSR-5	94	52	TT-1	3
D	PSR-6	78	60	TT-1	5
	PSR-7	94	77	TT-2	0.8
	PSR-8	115	72	TT-2	8.5

Table S10: Details of exploration targets at site D

S. N.	Latitude	Longitude	Diameter (m)	Depth (m)	Significance
1	-88.9662	-78.5222	495	45	Excavates de-Gerlache impact ejecta
2	-88.9473	-79.4565	1100	156	Excavates de-Gerlache impact ejecta
3	-88.9872	-79.4443	67	2	Excavates Shackleton ejecta
4	-88.9814	-84.6785	457	100	Excavates de-Gerlache impact ejecta

5	-88.9982	-84.5578	517	60	Excavates de-Gerlache impact ejecta
6	-88.9997	-87.7742	391	20	Excavates de-Gerlache impact ejecta
7	-89.0086	-89.4378	90	8	Excavates Shackleton ejecta
8	-89.007	-90.1183	336	20	Excavates de-Gerlache impact ejecta
9	-89.0007	-94.2611	90	4	Excavates Shackleton ejecta
10	-89.0039	-94.2751	115	7	Excavates Shackleton ejecta
11	-89.0044	-94.9423	274	23	Excavates de-Gerlache impact ejecta
12	-89.0073	-95.857	571	50	Excavates de-Gerlache impact ejecta

Table S11: Details of exploration targets at site C1

S.N.	Latitude (degree)	Longitude (degree)	Diameter (m)	Depth (m)	Significance
1	-89.4109	-131.3549	78	5	Excavates Shackleton ejecta
2	-89.4553	-135.5116	100	7	Excavates Shackleton ejecta
3	-89.4372	-136.2438	50	1	Excavates Shackleton ejecta
4	-89.4532	-137.8434	76	2	Excavates Shackleton ejecta
5	-89.4095	-135.2659	200	7	Excavates Shackleton ejecta
6	-89.4344	-138.5303	35	<1	Excavates Shackleton ejecta
7	-89.4027	-140.1537	610	37	Excavates Shackleton ejecta
8	-89.3595	-137.8912	1500	70	Excavates de-Gerlache ejecta
9	-89.3407	-137.6692	580	39	Excavates Shackleton ejecta

10	-89.3423	-139.065	330	28	Excavates Shackleton ejecta
11	-89.3674	-141.5445	60	4	Excavates Shackleton ejecta

Supplementary Figures

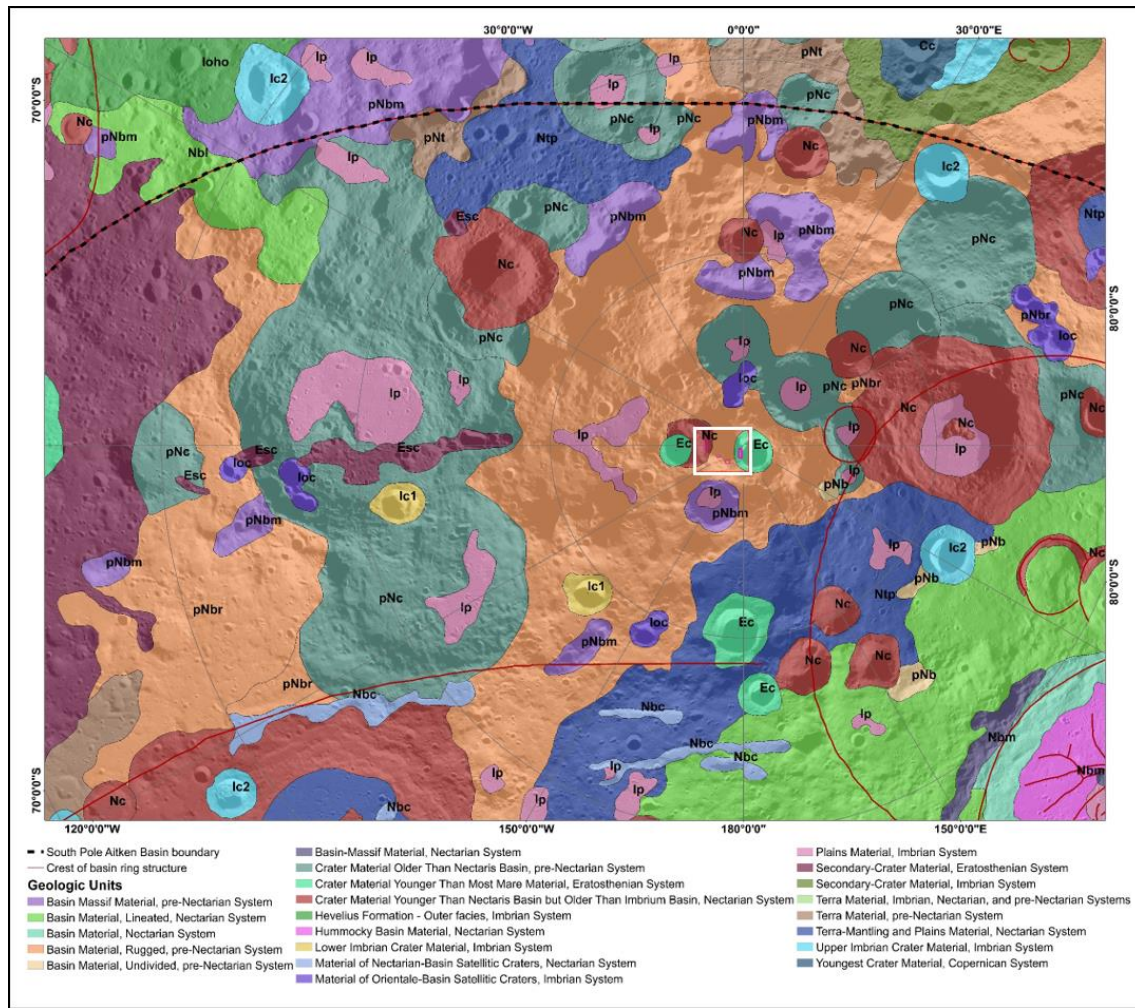


Figure S1. Geology map of lunar south polar region (Fortezzo et al., 2020). The area under study is represented by red rectangle. The landing sites S, C1, C2, and D are shown with magenta rectangles within the white rectangle.

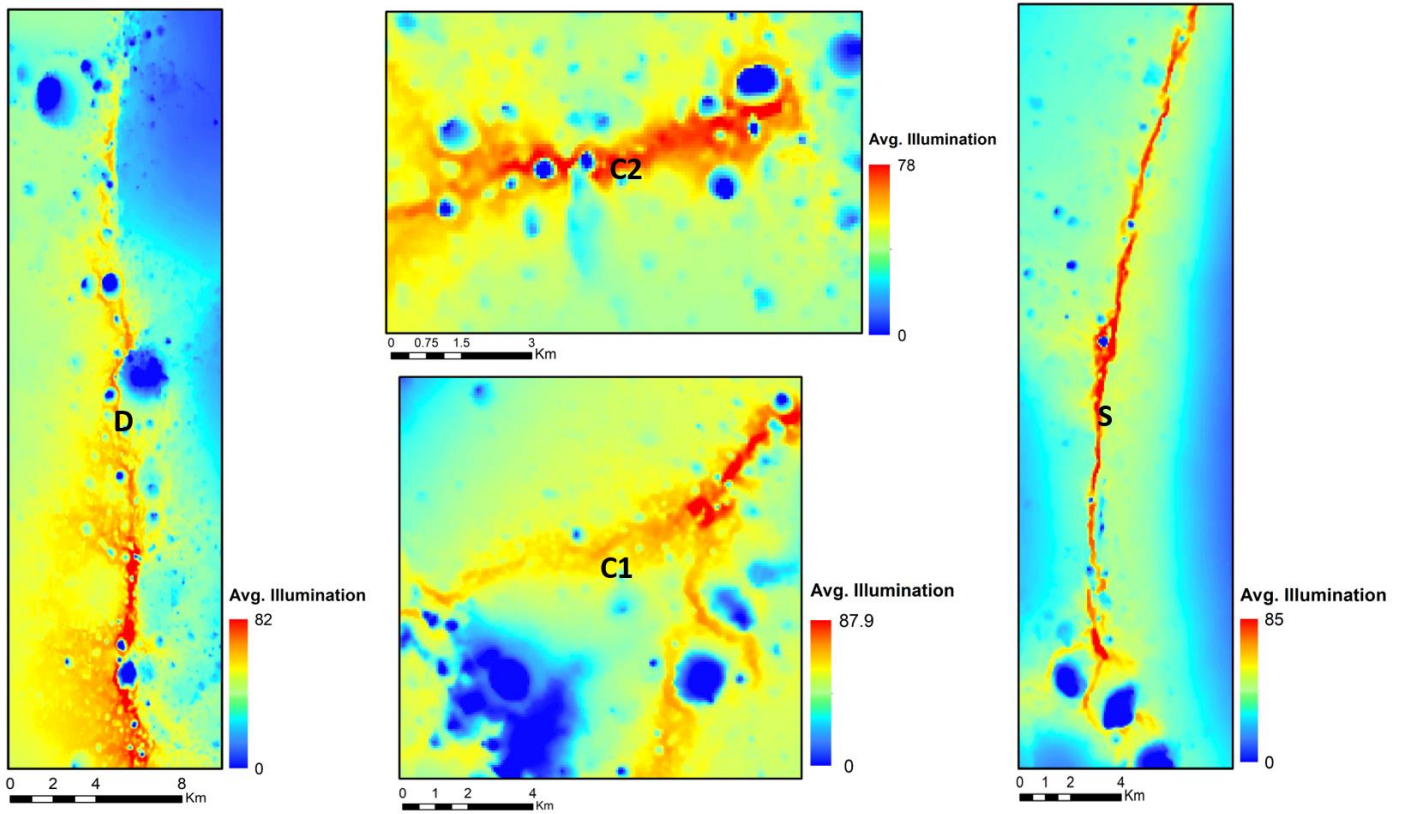


Figure S2. Illumination modelling results of landing sites at a 2m elevation level from the surface taking solar panel height into consideration.

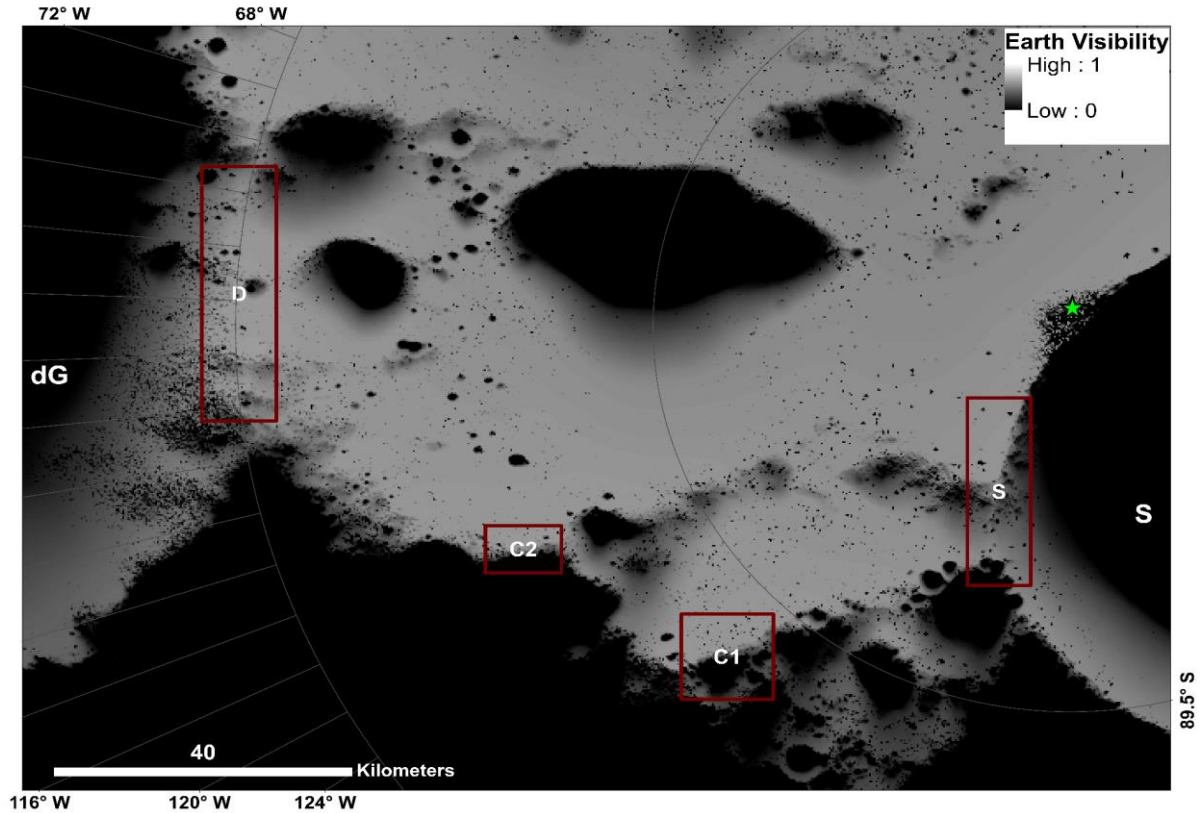


Figure S3. Earth visibility map derived from LOLA DEM based on Mazarico et al., 2011. Site D is the best for landing considering the excellent Earth visibility, an important parameter for direct communication with Earth through lander. Table S3 lists the percentage value of Earth visibility for each landing site.

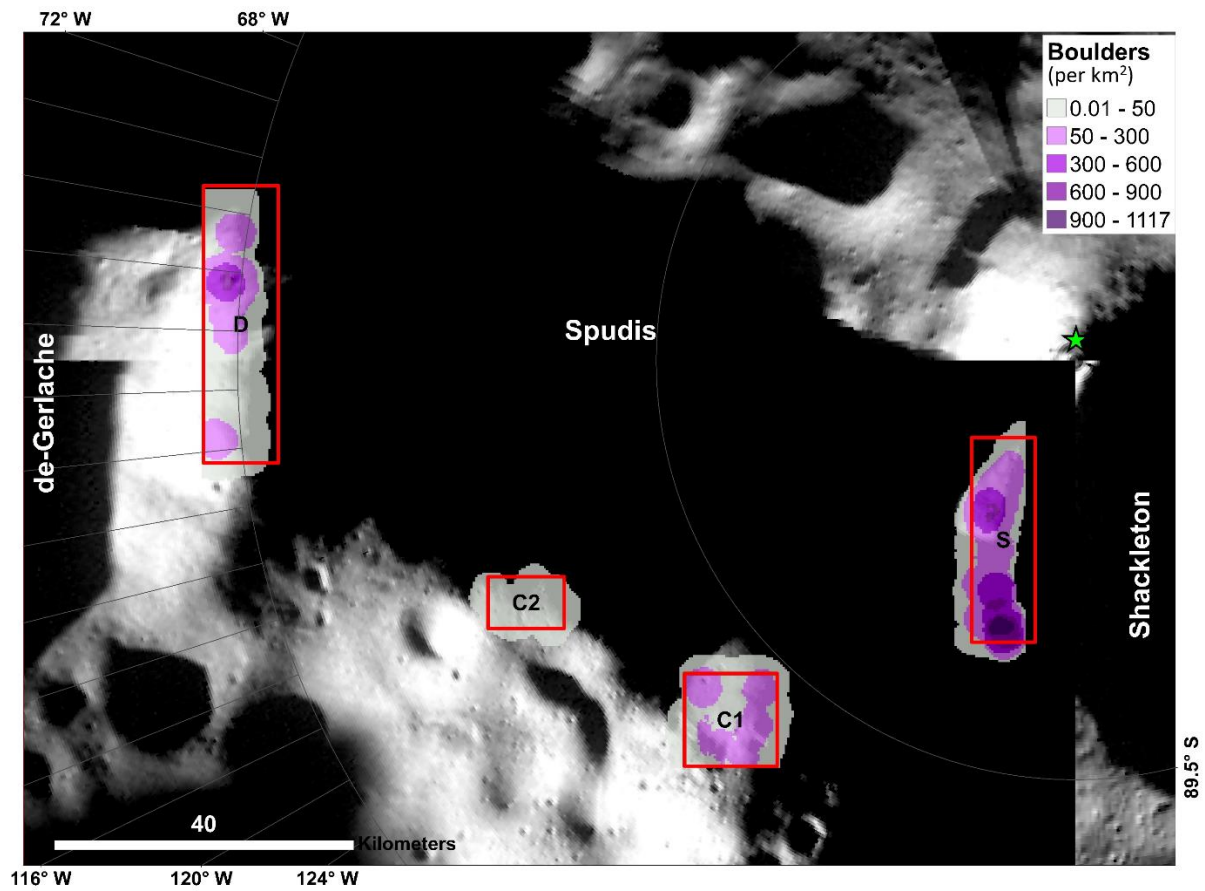


Fig S4. Boulder density map with a cell size of 80 m overlaid on LROC WAC mosaic for lunar south polar region.

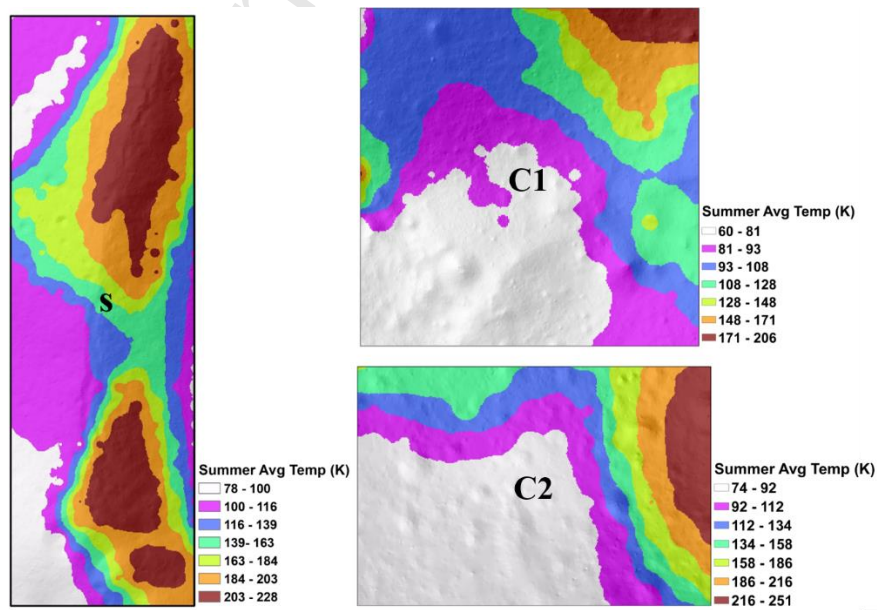


Figure S5. Diviner Summer Average temperature maps for Site S (a), C1 (b) and C2 (c) prepared by interpolating Diviner temperature points using IDW interpolation method.

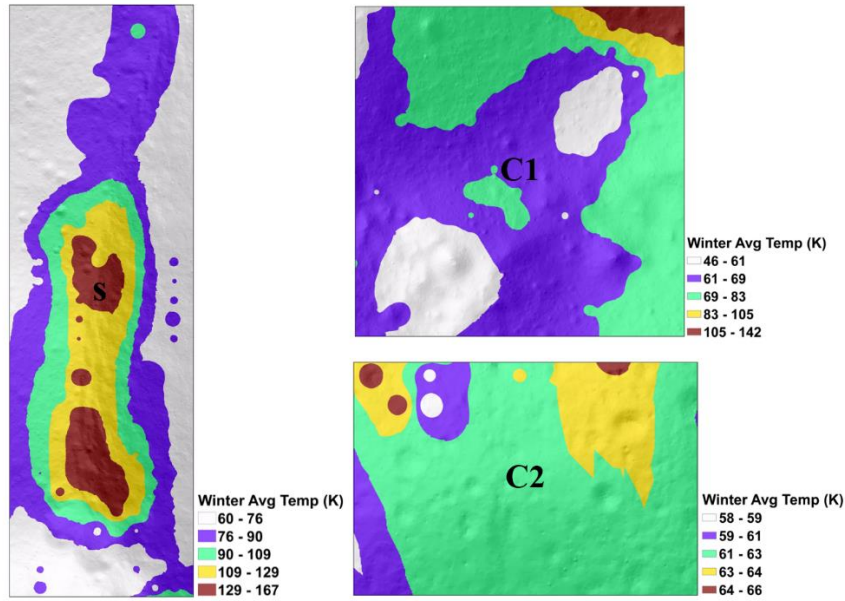


Figure S6. Diviner Winter Average temperature maps for Site S (a), C1 (b) and C2 (c) prepared by interpolating Diviner temperature points using IDW interpolation method.

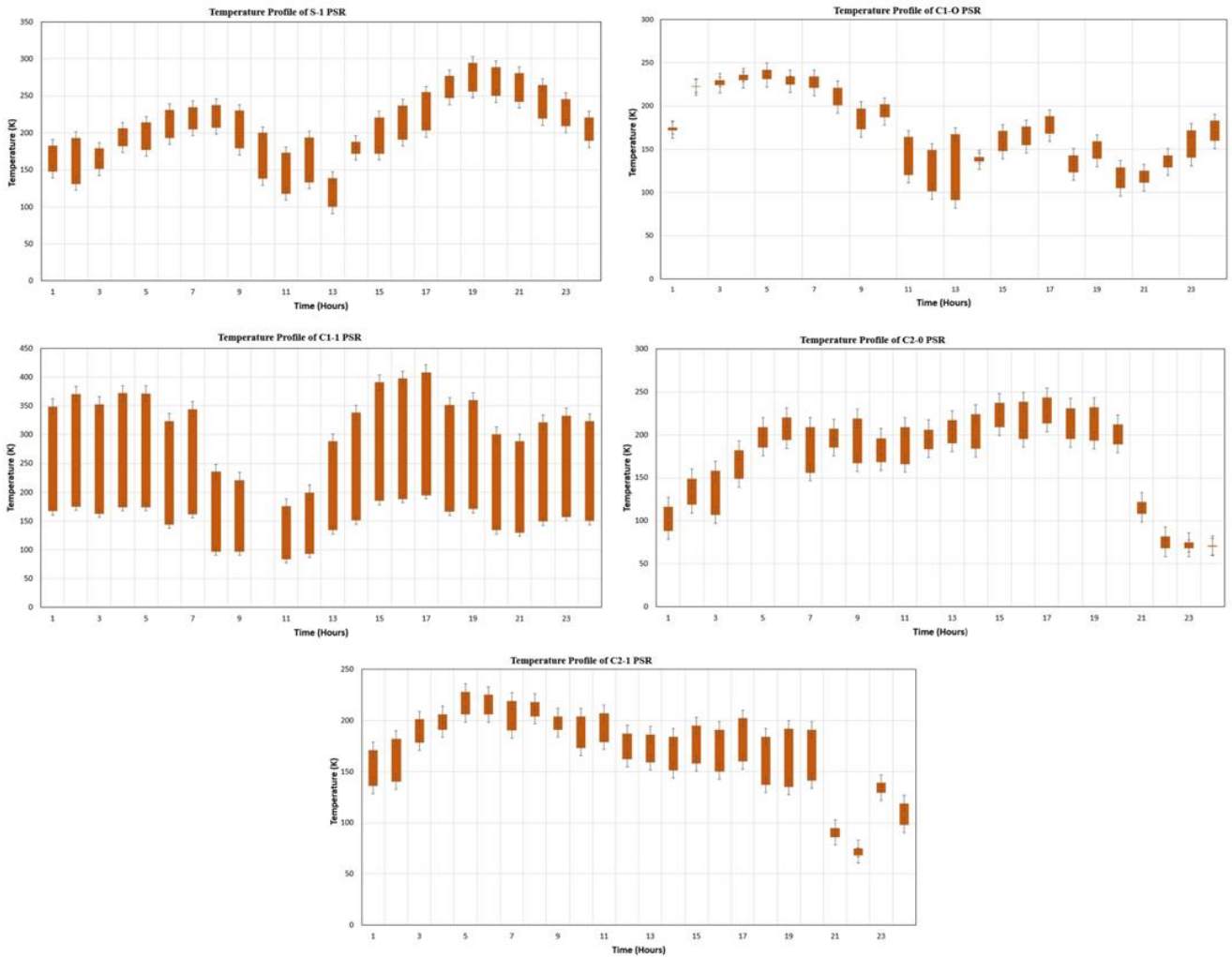


Fig S7. Diurnal temperature profiles for the PSR's detected by Gläser et al., 2018. PSR S-0 is omitted as it is already being discussed in main text.

Journal Pre-proof

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Highlights

- Landing site characterization of four highly illuminated sites on de Gerlache – Shackleton ridge is presented.
- Prioritization of the sites based on geotechnical parameters and feasibility to access a PSR for volatile detection and quantification.
- Landing and roving feasibility are analyzed by formulating a trafficability map.
- Selection of 2 optimum landing sites with maximum scientific advantages and rover traverse possibility.

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